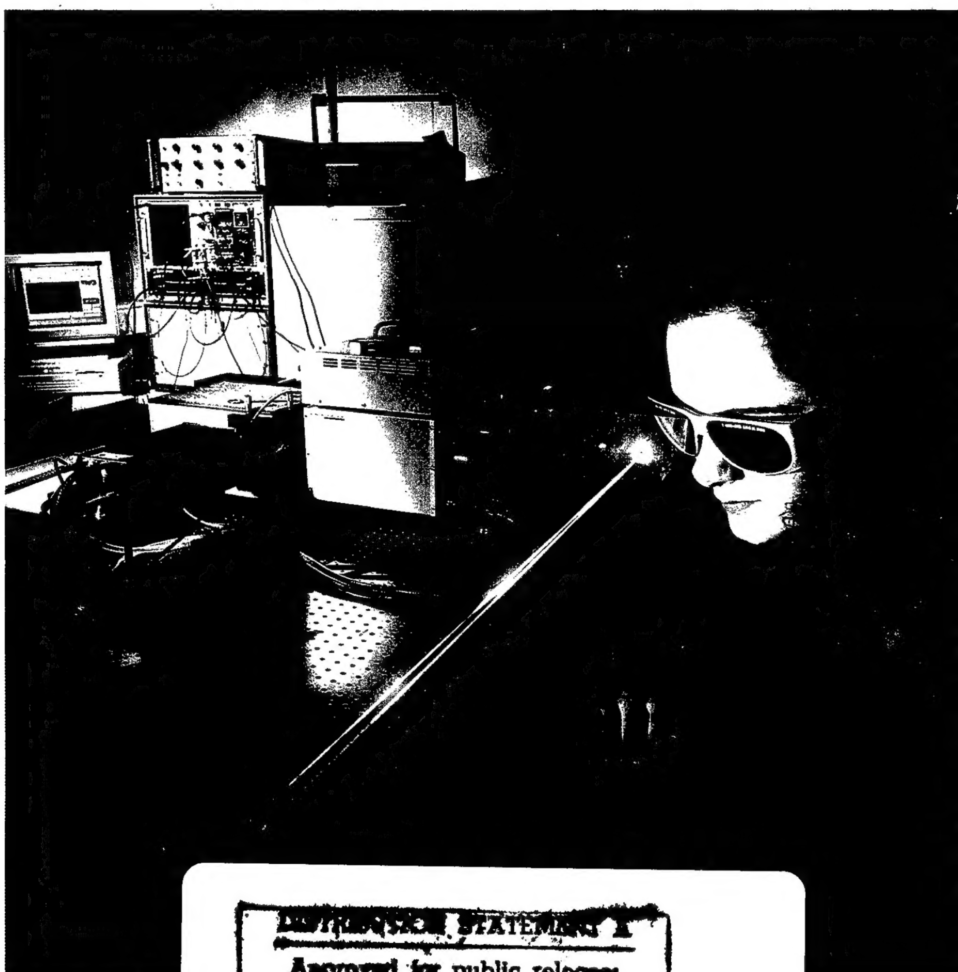
Institute *of* **Physics**

TECHNICAL DIGEST

NATIONAL QUANTUM ELECTRONICS CONFERENCE

QE 13



8 - 11 September 1997

University of Wales, Cardiff, Wales, UK

Technical Digest of Papers Presented at

THE THIRTEENTH UK NATIONAL QUANTUM ELECTRONICS CONFERENCE

University of Wales, Cardiff, 8-11 September 1997

organized by

The Quantum Electronics Group of the Institute of Physics

and hosted by

The Department of Physics and Astronomy, University of Wales, Cardiff,
in association with
The School of Electronic Engineering and Computing Systems, University of Wales, Bangor

Cardiff University of Wales

Prifysgol Cymru · University of Wales
BANGOR

CHAIRMAN'S FOREWORD

Welcome to QE-13 and to Cardiff: we hope you find the meeting scientifically productive and stimulating and that your visit here is an enjoyable one. With regard to the former, our thanks go to Alan Shore, the Programme Committee and the contributors of papers for their efforts to ensure the scientific value of the meeting and, as for enjoyment, thanks go to members of the Local Organising Committee for their advice and painstaking research throughout the summer in the cause of helping you have a good time. The effort to prepare for this conference has come primarily from constituent institutions of the University of Wales at Bangor, Cardiff and Swansea and we also thank Terry King and Bruce Sinclair of the Quantum Electronics Group Committee for their help, advice and encouragement.

Research presented at the Conference can be published in a special issue of the Journal of Modern Optics and we thank Peter Knight for his co-operation in this.

The Conference has received financial support from Coherent UK Ltd, US Army and Navy, Toshiba Cambridge Research Centre Ltd, and the University of Wales, and we are particularly indebted to the Welsh Development Agency, through the Welsh Optoelectronics Forum, for their generous help including provision of the Exhibition Reception to be held in the Exhibition Area on Tuesday. The Conference Dinner will be held in the City Hall at 8pm on Wednesday preceded by a Vice-Chancellor's Reception at 6.45pm in the Viriamu Jones Gallery on the ground floor of the Main College Building located between Park Place and Museum Avenue. All these locations are within easy walking distance which will provide you with the chance of some exercise .

Special thanks for their efforts on behalf of the Conference go to Alan Shore in Bangor for his work putting together the scientific programme, and to Cherrie Summers and Aderyn James in Cardiff for doing most of the remaining work, and that with professionalism and good cheer.

Peter Blood
Chairman
QE 13 Organizing Committee

QE'13 Programme Preface

The compilation of the programme for the QE Conference presents a very interesting challenge to its Programme Committee. This year that challenge has been given an extra dimension with the need to arrange the conference over a shorter period of time than in previous meetings in the QE series. This was a deliberate decision taken, on the advice of the IOP QE group, with a view to encouraging a higher attendance by the community which QE serves. It was recognised that with increasing pressures on their time it is often very difficult for active researchers to set aside a long period for such a meeting. It is hoped that the compact format adopted this year will prove beneficial in this respect whilst still providing sufficient scope for the informal interactions which, for many people, is a vital aspect of any meeting. In line with the aim of arranging a compact conference, it was decided to integrate the conference Workshop into the meeting rather than have it as an appendage to the main meeting. This has produced the only part of the meeting where parallel sessions were required.

In structuring the programme for QE'13 the Programme Committee had two main objectives. Firstly it aimed to increase the proportion of oral presentations at the meeting and at the same time it wished to maintain coherent themes within the scheduled oral and poster sessions. In reaching those objectives the Programme Committee also sought to have as many aspects as possible of the work of the QE community to be represented in oral sessions.Within the constraint of a relatively smaller number of available oral sessions (consequent to a reduction in length of the conference) it is believed that this aim has largely been achieved. However, it is for the community to decide whether the present approach meets its needs. Although we are confident that QE members will not hestitate to express their views on this matter it is wished to emphasise that constructive criticism of the work of the Programme Committee is not only welcomed but is positively solicited. The immediate beneficiaries of those comments will be the organiser of QE'14 but, of course, the ultimate beneficiary will be the QE community itself.

For work on the preparation of the Programme thanks go to Dr Steve Bland, EPI who organised the session on Industrial Applications of Lasers; to Dr Susan Dewar, Cardiff, and Dr Paul Rees, Bangor for their work organising the Workshop on Microcavities and Photonic Bandgaps . The Programme Committee has also benefited greatly from the advice of Prof. Terry King and Dr Bruce Sinclair as respectively Chair and Secretary of the QE group. The meeting is also grateful to the invited speakers for being prepared to contribute their special expertise to the meeting. The smooth running of the technical sessions will be the responsibility of the session chairs and thanks go to those members of the community who were prepared to contribute their services in this way. The programme, of course, only exists because of the exciting research being undertaken within the community and we are grateful for such vitality on the part both of paper presenters and authors and by delegates who will, we presume, make unscripted contributions to the meeting.

The Programme Committee (nor QE'13 itself) could not have functioned without the dedication, professionalism and organisational skills of Ms Cherrie Summers who always disclaims thanks but always deserves the highest praise for her efforts. Cherrie's contribution to QE'13 has not only included paying attention to a myriad of conference details but also keeping the Programme Committee chair in a positive frame of mind at critical times. For that I offer a personal word of thanks.

Professor K Alan Shore
Programme Committee Chair QE'13
University of Wales, Bangor
School of Electronic Engineering & Computer Systems

ACKNOWLEDGEMENTS

The local organizing committee wishes to thank the following organizations for the considerable support provided to QE 13:

Coherent UK Ltd
The European Research Office of the US Army and Navy
Toshiba Cambridge Research Centre Ltd
Vice Chancellor's Office of the University of Wales, Cardiff
The Welsh Optoelectronics Forum

QE 13 LOCAL ORGANIZING COMMITTEE

P Blood (Chair)
S Bland
S Dewar
S McMeekin
K A Shore
D Somerford
C Summers
H Telle

QE 13 PROGRAMME COMMITTEE

K A Shore (Chair)
S Barnett
C Danson
T A King
K Ridley
H Rutt
B D Sinclair
C Webb

SESSION CHAIRS

I. Laser Dynamics	W Sibbett
II. Spontaneous Emission	K A Shore
III. Laser Applications	C Danson
IV. Spectroscopy and Sensing	S Barnett
V. Coherent Processes	K Ridley
VI. Optically Pumped Lasers	D Hanna
VII. X Ray and TW Lasers	D R Hall
VIII. High Power and Parametric Effects	H Telle
IX. Industrial Application of Lasers	C Webb
X. Quantum Optics	G New
XI. Visible Emission	P Blood

SCOPE OF THE CONFERENCE

The Thirteenth UK National Quantum Electronics Conference (QE 13), organized by the Quantum Electronics Group of the Institute of Physics and hosted by the Department of Physics and Astronomy, University of Wales, Cardiff, will be held in the Trevithick Building from Monday 8 to Thursday 11 September, 1997. The scope of the topics to be covered includes:

The physics of coherent light sources
New laser systems
Non-linear and quantum optics
Laser spectroscopy
Application of lasers

The conference will also feature a Technical Exhibition, a Workshop on Microcavities and Photonic Bandgaps and a special Industrial Session, as well as laboratory tours.

OFFICIAL CONFERENCE ADDRESS

QE 13 Conference Secretariat
Cardiff School of Engineering
PO Box 917
Newport Rd
Cardiff CF2 1XH

Tel: 44 (0) 1222 874000
Fax: 44 (0) 1222 874421
Email: SummersC@Cardiff.ac.uk

WORKSHOP: Microcavities and Photonic Bandgaps

The conference will include a workshop on Microcavities and Photonic Bandgaps on Wednesday afternoon at 4pm in the Faculty Lecture Theatre, Trevithick Building.

POSTER SESSION

The Poster Session will take place in the Seminar Rooms 1 and 2. Posters should be posted onto the poster boards on Tuesday morning and the Poster Room will be open throughout the conference to give all delegates the opportunity to read the papers. However, there will be a special Poster Session on Tuesday at 5.30 when poster presenters will need to be present to discuss their posters.

Please see the staff at the registration desk for help and advice on arranging your poster papers.

AGM OF THE QUANTUM ELECTRONICS GROUP

The AGM will be held at 12.30 in the Prince Phillip Lecture Theatre on Tuesday.

A Committee Meeting of the QE Group will take place in the Tredegar Room at the Staff Club in Park Place at 7.30 pm following the Exhibition Drinks and Poster Session. Dinner will be provided for committee members. Check at the registration desk for directions.

REGISTRATION DESK

The registration desk will be staffed throughout the conference. It will open at 8.30 am each morning and will close at 6pm. Please feel free to seek assistance from the staff at any time.

PUBLICATION OF PAPERS

Participants are encouraged to contribute their papers to a special issue of the Journal of Modern Optics devoted to conference papers. Contributors should submit papers to the Registration Desk. Professor P L Knight at Imperial College is the Guest Editor. All contributions will be subject to additional review by a single referee.

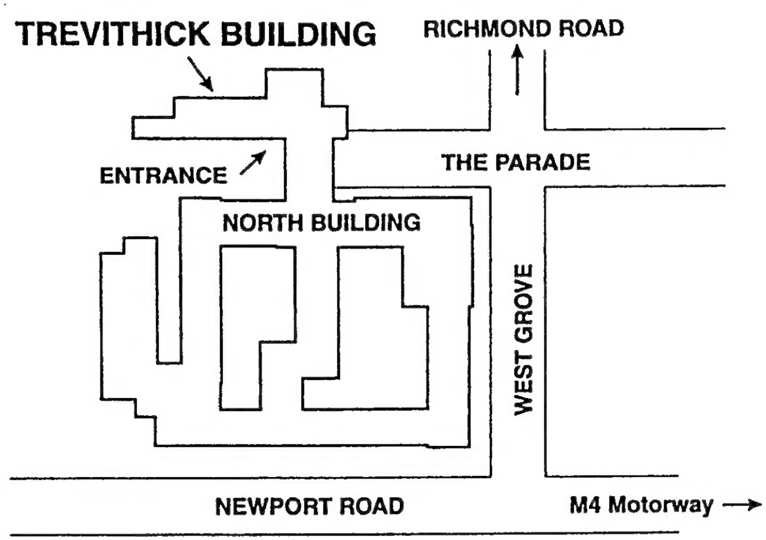
TECHNICAL EXHIBITION

An exhibition of optoelectronic and laser equipment is being held in conjunction with the conference. The Exhibition will take place in the Junior Common Room in the Trevithick Building from 9am Tuesday to 2pm Thursday, and delegates will have access to the Exhibition during the conference hours. The opening reception, which is sponsored by the Welsh Optoelectronics Forum, will take place on Tuesday evening in the JCR at 5.30pm. All delegates are welcome.

The following companies are exhibiting:

Bentham Instruments Ltd
Burleigh Instruments Ltd
Cambridge Lasers Ltd
Edinburgh Instruments Ltd
Elliot Scientific Ltd
Epitaxial Products International Ltd
Lambda Photometrics Ltd
Laser 2000
Laser Instrumentation Ltd
Laser Lines Ltd
Laser Support Services
Melles Griot
Newport Ltd
Photon Technology International
Swift Technology Services
Volga Technology
Welsh Optoelectronic Forum

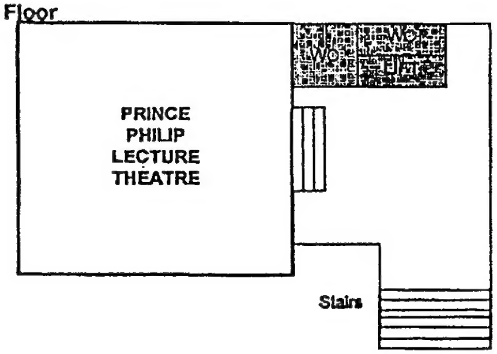
Map: Location of Trevithick building



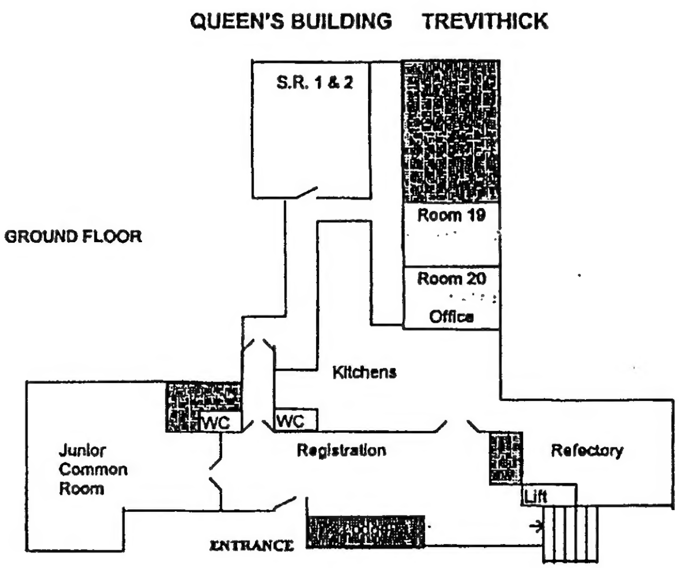
NORTH BUILDING

Across from Second Floor Trevithick Building

Fourth Floor



Map: Queen's Building, Trevithick



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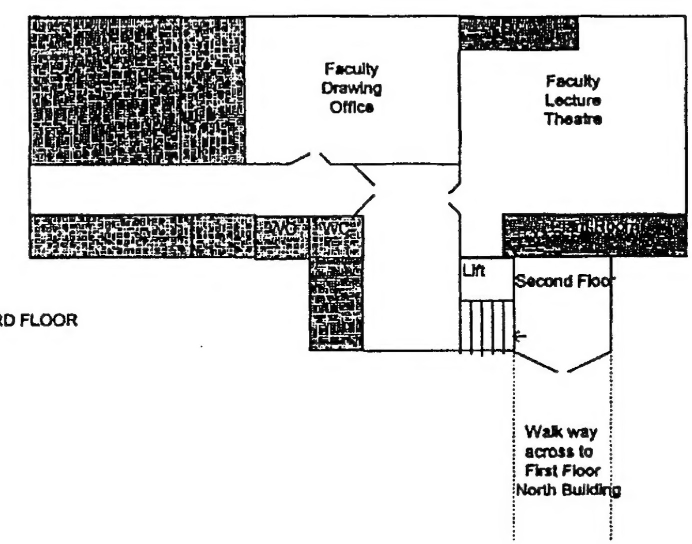

THIRD FLOOR

Quantum Electronics Conference (QE 13) Programme Summary

All technical sessions will take place in the **Prince Phillip Lecture Theatre (North Blding)** unless otherwise specified.

TIME	TUESDAY 9 SEPT	WEDNESDAY 10 SEPT	THURSDAY 11 SEPT
8.30	**Registration: Trevithick Foyer**	**Registration: Trevithick Foyer**	**Registration: Trevithick Foyer**
8.45	Opening Remarks		
9.00	Laser Dynamics. Chair: W Sibbett	Invited Speaker: M Padgett	IX Industrial Application of Lasers Chair: C Webb
9.30		V: Coherent Processes Chair: K Ridley	
10.30	**Coffee and Exhibition JCR**	**Coffee and Welshcakes sponsored by Coherent. Exhibition JCR**	**Coffee and Exhibition JCR**
11.00	Invited Paper: P Gourley	Invited Speaker: G Parry	Invited Paper: E Rosencher
11.30	II: Spontaneous Emission Chair: K A Shore	VI:Optically Pumped Lasers Chair: D Hanna	X: Quantum Optics Chair: G New
12.30	**Lunch and Exhibition Refectory and JCR**	**Lunch and Exhibition Refectory and JCR**	**Lunch and Exhibition Refectory and JCR**
14.00	III: Laser Applications Chair: C Danson	VII: X Ray and TW Lasers Chair: D R Hall	Invited Paper: E Hinds
14.30			XI: Visible Emission Chair: P Blood
15.30	**Tea and Exhibition JCR**	**Tea and Exhibition JCR**	
16.00	IV: Spectroscopy and Sensing Chair: S Barnett	VIII:High Power and Parametric Effects, Chair H Telle, OR	**Tea and Lab Tours JCR**
		Workshop on Photonic Bandgaps Lecture Theatre on 2nd Floor	
17.30	**Poster Session and Exhibition Drinks Reception - JCR and SR 1 and 2**		Bus to the Station
18.45		**Drinks Reception at Viriamu Jones Gallery**	
20.00		**Conference Dinner at City Hall**	

QE'13 PROGRAMME

TUESDAY 9 SEPTEMBER 1997

0845 Introductory Remarks
0900 SESSION 1. LASER DYNAMICS

1. NOVEL Q-SWITCHING OF A MICROCHIP LASER USING A QUADRAPOLE DEFLECTOR
   J. Ley *, R.S. Conroy, A.J. Kemp, G.J. Friel, B.D. Sinclair, J.F. Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, Scotland, KY16 9SS, UK.
   * Leysop Ltd., Basildon, Essex, England, UK.

2. A HIGH POWER Q-SWITCHED ERBIUM FIBRE LASER PRODUCING 50μJ PULSES
   H.H. Kee, G.P. Lees, D. Taverner, D.J. Richardson, T.P. Newson, Optoelectronics Research Centre, University of Southampton Southampton, SO17 1BJ.

3. EXPERIMENTAL AND THEORETICAL BEHAVIOUR OF ALL-SOLID-STATE KERR-LENS MODE-LOCKED LASERS
   A. Ritsataki, G.H.C. New, R. Mellish, J. Plumridge, P.M.W. French and J.R. Taylor, Laser Optics and Spectroscopy Group, Department of Physics, Imperial College, London, SW7 2BZ, UK.

4. COMPRESSED 200FSEC PULSES FROM A SYNCHRONOUSLY PUMPED OPTICAL PARAMETRIC OSCILLATOR IN PERIODICALLY-POLED LITHIUM NIOBATE
   S.D. Butterworth, L. Lefort and D.C. Hanna, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK.

5. DYNAMICS OF THREE-LEVEL SYSTEMS
   D.C. Hutchings, University of Glasgow.

6. PULSED SINGLE-MODE LASERS IN MULTI-MIRROR GRAZING INCIDENCE CAVITIES
   D.J. Binks, L.A.W. Gloster and T.A. King, Laser Photonics Group, Department of Physics and Astronomy, University of Manchester, M13 9PL, UK. D.K. Ko, Laboratory for Quantum Optics, Korea Atomic Energy Research Institute, PO Box 105, Taejon 305-600, Korea.

10.30 COFFEE

11.00 INVITED PAPER : "MICRO-LASER OPTICAL MECHANICAL DEVICES FOR BIOMEDICAL APPLICATIONS" P.Gourley, Sandia Laboratory, NM, USA

11.30 SESSION 2. SPONTANEOUS EMISSION CONTROL

1. MOLECULAR FLUORESCENCE ABOVE PLANAR AND CORRUGATED METALLIC FILMS
   R.M. Amos*, W.L. Barnes, Department of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK.
   * Current address: DERA, St. Andrews Road, Malvern, Worcs. WR14 3PS, UK.

2. MEASUREMENTS OF THE SPONTANEOUS EMISSION FROM SINGLE DYE MOLECULES IN A MICROCAVITY
   S.C. Kitson, P. Jonsson*, J.G. Rarity and P.R. Tapster, DERA, St. Andrews Road, Malvern, Worcs., WR14 3PS, UK.

3. MODIFICATION OF SPONTANEOUS EMISSION BY DIELECTRIC MEDIA
   Stephen M. Barnett, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, Scotland. Rodney Loudon, Department of Physics, University of Essex, Colchester, CO4 3SQ, UK. Reza Matloob, Department of Physics, University of Kerman, Kerman, Iran.

4. IMPROVED PHOTON NUMBER SQUEEZING IN LIGHT EMITTING DIODES
   F. Wölfl, G.-M. Schucan, A.M. Fox and J.F. Ryan, University of Oxford, Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.

12.30 LUNCH AND EXHIBITION TIME

14.00 SESSION 3. LASER APPLICATIONS

1. PROGRESS TOWARDS A LASER GUIDE STAR SYSTEM FOR USE IN ASTRONOMICAL ADAPTIVE OPTICS
   H.J. Booth, G.P. Hogan and C.E. Webb, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.

2. DIFFRACTIVE OPTICAL ELEMENTS FOR LASER ENGINEERING AND MATERIAL PROCESSING APPLICATIONS
   P. Blair, M.R. Taghizadeh, A.J. Waddie, H.J. Baker and D.R. Hall, Physics Department, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK.

3. A NOVEL TECHNIQUE FOR INTERFEROMETRIC SURFACE PROFILING WITHOUT FRINGE AMBIGUITY
   J.P. Lesso, A.J. Duncan, W. Sibbett and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, St. Andrews, KY16 9SS, UK.

4. A NOVEL METHOD OF INCREASING THE RANGE OF 1.65μm OTDR USING A Q-SWITCHED ERBIUM FIBRE LASER
   Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ.

5. A SINGLE PHOTON COUNTING TIME-OF-FLIGHT IMAGING SYSTEM
   J.S. Massa, N. Perrimon, G.S. Buller and A.C. Walker, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK. M. Umasuthan and A.M. Wallace, Department of Computing and Electrical Engineering, Heriot-Watt University, Edinburgh, EH14 4AS, UK.

6. GALLIUM LANTHANUM SULPHIDE BASED GLASS FIBRES FOR PASSIVE MIR DELIVERY APPLICATIONS
   D.J. Brady, T. Schweizer, J. Wang, D.W. Hewak, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ

15.30 TEA

1600 : SESSION 4. SPECTROSCOPY AND SENSING

1. SPECTROSCOPY OF A SINGLE YTTERBIUM ION
   P. Taylor, M. Roberts, G.P. Barwood, H.A. Klein, W.R.C. Rowley and P. Gill, Centre for Dimensional Metrology, National Physical Laboratory, Queens Road, Teddington, Middlesex, TW11 OLW.

2. TIME-RESOLVED SPECTROSCOPY OF PLASMAS GENERATED BY COPPER VAPOUR LASER ABLATION OF METALS
   D. Kapitan, D.W. Coutts and C.E. Webb, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU.

3. A SUB-1 kHz LINEWIDTH PROBE LASER FOR INTERROGATING THE $^2S_{1/2}$ - $^2D_{5/2}$ TRANSITION IN COLD TRAPPED STRONTIUM IONS
   G.P. Barwood, P. Gill, G. Huang, H.A. Klein and W.R.C. Rowley, Centre for Dimensional Metrology, National Physical Laboratory, Queens Road, Teddington, Middlesex, TW11 OLW.

4. THE APPLICATION OF A CONTINUOUSLY-TUNABLE, CW OPTICAL PARAMETRIC OSCILLATOR FOR HIGH RESOLUTION SPECTROSCOPY
   G.M. Gibson, M.H. Dunn and M.J. Padgett, J.F. Allen Research Laboratories, School of Physics and Astronomy, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland.

5. PROGRESS TOWARDS MID-INFRARED FIBRE LASERS IN RARE-EARTH DOPED GALLIUM LANTHANUM SULPHIDE GLASS FOR GAS SENSING AND REMOTE SENSING
   T. Schweizer, D.J. Brady, B.N. Samson, D.W. Hewak, and D.N. Payne, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ.

6. PROGRESS ON THE DEVELOPMENT OF AN ULTRA-VIOLET STATIC FOURIER-TRANSFORM SPECTROMETER FOR THE DETECTION OF TOXIC GASES
   B.A. Patterson, J. Lenney*, W. Hirst#, W. Sibbett and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, KY16 *Siemens Environmental Systems, Sopers Lane, Poole, BH17 7ER. #Shell Research Limited, Thornton, CH1 3SH.

1800 POSTER SESSION /EXHIBITION TIME/RECEPTION

Wednesday 10 SEPTEMBER 1997

0900 INVITED PAPER: OPTICAL TWEEZERS, SPANNERS AND LAGUERRE-GAUSSIAN LASER MODES, Miles Padgett. The University of St. Andrews.

09.30 SESSION 5. COHERENT PROCESSES

1. COHERENTLY INDUCED TRANSPARENCY AND INVERSIONLESS GAIN ON A BLUE PROBE IN A DOPPLER-BROADENED V-TYPE MEDIUM
   D.J. Fulton, J.R. Boon, E. Zekou, S. Shepherd and M.H. Dunn, J.F. Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, KY19 9SS, Scotland, UK.

2. INVESTIGATION OF THE ROLE OF EIT IN FOUR-WAVE MIXING IN Kr
   C. Dorman, J.P. Marangos and J.C. Petch, Laser Optics and Spectroscopy Group, Blackett Laboratory, Imperial College, London, SW7 2B

3. STIMULATED BRILLOUIN SCATTERING WITH AN INFRA-RED OPTICAL PARAMETRIC OSCILLATOR
   K.D. Ridley, Defence Research Agency, St. Andrews Road, Great Malvern, Worcestershire, UK.

4. DYNAMICS OF ORIENTATIONALLY ENHANCED POLYMERIC PHOTOREFRACTIVE COMPOSITES
   K.S. West, J.D. Shakos, A.M. Cox, D.P. West and T.A. King, Laser Photonics Group, University of Manchester, Manchester, M13 9PL. R.D. Blackburn, Liverpool John Moores University Byrom Street, Liverpool, L3 3AF.

10.30 COFFEE

11.00 INVITED SPEAKER G.PARRY

11.30 SESSION 6. OPTICALLY PUMPED LASERS

1. Ti:SAPPHIRE LASERS TRANSVERSELY PUMPED WITH A HIGH POWER COPPER VAPOUR LASER
   W.J. Wadsworth, D.W. Coutts and C.E. Webb, University of Oxford, Atomic and Laser Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU.

2. A 2 W 6.2 Hz FIBRE-END-PUMPED TITANIUM SAPPHIRE LASER
   A.J.S. McGonigle and D.W. Coutts, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.

3. THERMAL LENSING IN HIGH-POWER END-PUMPED Nd: YLF LASERS
   P.J. Hardman, M. Pollnau, W.A. Clarkson, and D.C. Hanna, Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ.

4. THEORY AND DEVELOPMENT OF A DIODE LASER PUMPED 2.8-μm CW Er:YLF LASER
   M. Tikerpae, S.D. Jackson and T.A. King, Laser Photonics Group, University of Manchester, Manchester, M19 2GR.

5. EFFICIENT CW AND Q-SWITCHED OPERATION OF A 946nm Nd:YAG LASER PUMPED BY AN INJECTION-LOCKE BROAD AREA SEMICONDUCTOR LASER
   I.D. Lindsay, M.H. Dunn and M. Ebrahimzadeh, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, KY16 9SS, UK.

6. EFFICIENT 1123nm DIODE-BAR PUMPED Nd: YAG LASER
   N. Moore, W.A. Clarkson, D.C. Hanna, Optoelectronics Research Centre, Southampton, SO17 1BJ, UK.
   S. Lehmann, J. Bosenberg, Max Planck Institut fur Meteorologie, 20146 Hamburg, Germany.

1300 LUNCH AND EXHIBITION TIME

1400-1800 WORKSHOP : Microcavities and Photonic Bandgaps (details below)

1400 SESSION 7. X RAY AND TW LASERS

1. AN ADVANCED PULSE GENERATOR AND PREAMPLIFIER FOR THE HELEN LASER
   M.J. Norman, E.J. Harvey, N.W. Hopps, J.R. Nolan, AWE plc, Aldermaston, Reading, Berkshire, RG7 4PR, UK.

2. NEW DEVELOPMENTS IN Ni-LIKE X-RAY LASERS AT RAL
   J. Zhang [1], A. MacPhee[2], J. Lin[3], E. Wolfrum[1], J. Nilsen[4], T.W. Barbee, Jr.[4], C. Danson[5], M.H. Key[4], C.L.S. Lewis[2], D. Neely[5], R.M.N. O'Rourke[2], G.J. Pert[6], R. Smith[3], G.J. Tallents[3], J.S. Wark[1].
   [1] Clarendon Laboratory, Department of Physics, University of Oxford, Oxford, OX1 3PU.
   [2] Department of Pure and Applied Physics, Queens University, Belfast, BT7 1NN.
   [3] Department of Physics, University of Essex, Colchester, CO4 3SQ.
   [4] Lawrence Livermore National Laboratory, Livermore, California 94550, USA.
   [5] Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Oxon, OX11 OQX.
   [6] Department of Computational Physics, University of York, York, YO1 5DD.

3. MEASUREMENT OF DIRECT DRIVE LASER IMPRINT IN THIN FOILS BY XUV RADIOGRAPHY USING AN X-RAY LASER BACKLIGHTER
E. Wolfrum, J. Wark, J. Zhang, Clarendon Laboratory, University of Oxford, Oxford, UK.
D. Kalantar, M.H. Key, B.A. Remington, S.V. Weber, Lawrence Livermore National Laboratory, Livermore, California, USA. J. Warwick, A. Macphee, C.L.S. Lewis, Department of Pure and Applied Physics, Queens University, Belfast, UK. D. Neely, S. Rose, Central Laser Facility, Rutherford Appleton Laboratory, Didcot, UK. A. Demir, J. Lin, R. Smith, G.J. Tallents, Department of Physics, University of Essex, Colchester, UK.

4. FREQUENCY DOUBLING OF PICOSECOND PULSES ON THE VULCAN LARGE APERTURE CHIRPED PULSE AMPLIFICATION LASER SYSTEM
D. Neely, M. Trentelman, C.N. Danson, C. Beckwith, C.L. McCoard, J.L. Collier, C.B. Edwards, D.A. Pepler, M. Stainsby, F.N. Walsh, Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 OQX UK.

5. VULCAN: A UNIQUE SYSTEM DELIVERING 250 TW AND FOCUSED TO GIVE INTENSITIES OF 10^{20} Wcm^{-2}
C.N. Danson, S. Angood, L. Barzanti, J. Collier, A. Damerell, C.B. Edwards, S. Hancock, P. Hatton, M.H.R. Hutchinson, M.H. Key, W. Lester, C. McCoard, D. Neely, D.A. Pepler, C. Reason, D.A. Rodkiss, I.N. Ross, W. Toner, M. Trentelman, F.N. Walsh, T.B. Winstone, E. Wolfrum, R.W.W. Wyatt and B. Wyborn, Central Laser Facility, Rutherford Application Laboratory, Chilton, Didcot, Oxon, OX11 OQX, UK.

6. THE VULCAN LASER SYSTEM 250 TW UPGRADE - ULTRA HIGH POWER PULSE DIAGNOSTICS
J. Collier, D.A. Pepler, C.N. Danson, D. Neely, R. Allot, M. Trentelman, C. McCoard, I.N. Ross, C.B. Edwards, T.B. Winstone, J. Elwood, P. Exley, D. Hitchcock, C. Beckwith, M. Stainsby, Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 OQX, UK.

15.30 TEA

1600 SESSION 8. HIGH-POWER AND PARAMETRIC EFFECTS

1. BEAM CHARACTERISTICS OF AN ANNULAR CO_2 LASER
J.W. Bethel, H.J. Baker, D.R. Hall, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK.

2. GENERATION AND PROPAGATION OF HARMONICS USING BESSEL-GAUSS BEAMS
C.F.R. Caron and R.M. Potvliege, University of Durham, Physics Department, Durham, DH1 3LE, UK.

3. HIGH POWER, CONTINUOUS-WAVE, SINGLY-RESONANT, INTRACAVITY OPTICAL PARAMETRIC OSCILLATOR
T.J. Edwards, G.A. Turnbull, M.H. Dunn and M. Ebrahimzadeh, J.F. Allen Physics Research Laboratories, School of Physics and Astronon. University of St. Andrews, Fife, KY16 9SS. F.G. Colville, Tunable Laser Technology Ltd., Riccarton, Currie, Edinburgh, EH14 4AP, U

4. FEMTOSECOND OPTICAL PARAMETRIC OSCILLATOR BASED ON PERIODICALLY POLED LITHIUM NIOBATE
C. McGowan, D.T. Reid, Z.E. Penman, M. Ebrahimzadeh and W. Sibbett, J.F. Allen Research Laboratories, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, Scotland, KY16 9SS, UK. D.H. Jundt, Crystal Technology Inc., 1040 E. Meadow Cir., Palo Alto, CA 94303, USA.

5. ALTERNATIVE MEDIA AND COMPETING PROCESSES IN ULTRA-BROADBAND LIGHT GENERATION
G.S. McDonald, Y.M. Chan and G.H.C. New, Laser Optics and Spectroscopy Group, The Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London, SW7 2BZ, UK. L.L. Losev and A.P. Lutsenko, P.N. Lebedev Physical Institute Leninsky Prospekt 53, 117924 Moscow.

6. EFFICIENT OPERATION OF A SYNCHRONOUSLY-PUMPED OPTICAL PARAMETRIC OSCILLATOR IN PERIODICALLY-POLED LITHIUM NIOBATE OVER THE RANGE 1.33μm - 4.8μm
S.D. Butterworth, L. Lefort, K. Puech, P.G.R. Smith and D.C. Hanna, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ.

7. HIGH HARMONIC GENERATION AND PERIODIC LEVEL CROSSINGS
F.I. Gauthey, B.M. Garraway, and P.L. Knight, Optics Section, Blackett Laboratory, Imperial College, London, SW7 2BZ, UK.

8. CONTROLLING PATTERNS AND TURBULENCE IN NONLINEAR OPTICAL SYSTEMS
R. Martin, G.K. Harkness, A.J. Scroggie, G.L. Oppo and W.J. Firth, Department of Physics and Applied Physics, Universityof Strathclyde, Glasgow, G4 ONG, UK.

1800 EXHIBITION TIME AND RECEPTION

2000 CONFERENCE DINNER

THURSDAY 11 SEPTEMBER 1997

0900 : SESSION 9. INDUSTRIAL APPLICATION OF LASERS

1. **INVITED PAPER:** "MICROPROCESSING APPLICATIONS OF PULSED LASERS TO MANUFACTURING INDUSTRY" Dr. M. Gower, Exitech Ltd., Hanborough Park, Long Hanborough, Oxford, OX8 8LH.
2. **INVITED PAPER:** A. Raven, D. Fernie, Diomed
3. **INVITED PAPER:** "INDUSTRIAL LASER FACT FINDING MISSION TO JAPAN AND KOREA" - J.M. Green, AILU.

10.30 COFFEE

11.00 INVITED PAPER : " SEMICONDUCTOR HETEROSTRUCTURES:A QUANTUM LEGO FOR THE INFRARED"
-E. Rosencher, Laboratoire Central de Recherches de THOMSON-CSF ORSAY

1130: SESSION 10. QUANTUM OPTICS

1. WAVE PACKET DYNAMICS IN MOLECULES SUBJECTED TO INTERACTIONS WITH LIGHT
B.M. Garraway, Optics Section, Blackett Laboratory, Imperial College, London, SW7 2BZ, UK and K.-A.Suominen, Theoretical Physics Division, Department of Physics, University of Helsinki, PL9, FIN-00014, Finland.

2. OPTICAL MEASUREMENT BY PROJECTION SYNTHESIS
L.S. Phillips, S.M. Barnett and D.T. Pegg, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, Scotland.

3. PHYSICAL IMPLEMENTATION OF QUANTUM ALGORITHMS
Iain Gourlay, John F. Snowdon, Department of Physics, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS.

4. APPROXIMATE CONSTRUCTION OF QUANTUM STATES USING SUPERPOSITONS OF A FEW COHERENT STATES
L.K. Stergioulas(1) and A. Vourdas(2)
(1) Department of Engineering, The University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ.
(2) Department of Electrical Engineering and Electronics, The University of Liverpool, Brownlow Hill, P.O. Box 147, Liverpool, L69 3BX.

5. MICROMASER CAVITY FIELDS AND THEIR QUANTUM MEASUREMENTS
Amitabh Joshi(1, 2) and R.K. Bullough(1)
(1) Dept. of Maths, UMIST, P.O. Box 88, Manchester, M60 1QD
(2) L & PT Division, BARC, Bombary 400-085, India

6. ENTANGLED STATES AND NOVEL QUANTUM MEASUREMENTS
Anthony Chefles and Stephen M. Barnett, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG.

1300 LUNCH

14.00 INVITED PAPER : " ATOM OPTICS ", E. Hinds, University of Sussex

14.30 SESSION 11. VISIBLE EMISSION

1. OPTICAL FREQUENCY CHAIN AT NPL:PROGRESS AND PROSPECTS
S.N. Lea, G.M. Macfarlane, G. Huang and P. Gill, Centre for Dimensional Metrology, National Physical Laboratory, Queens Road, Teddington, Middlesex, TW11 OLW.

2. HIGH PERFORMANCE OXYGEN-FREE SOLID-STATE DYE LASERS
Mark D. Rahn and Terence A. King, Laser Photonics Group, Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL.

3. HIGH-POWER DIODE-BAR-PUMPED INTRACAVITY-FREQUENCY-DOUBLED ND: YAG AND ND: YLF RING LASERS
P.J. Hardman, W.A. Clarkson, K.I. Martin and D.C. Hanna, Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ.

4. THULIUM-DOPED UPCONVERSION FIBRE-LASER WITH 230mW of 480nm BLUE OUTPUT
R. Paschotta, N. Moore, W.A. Clarkson, A.C. Tropper, D.C. Hanna, Optoelectronics Research Centre, Southampton, UK. G. Maze, Le Verre Fluore, Campuu Ker Lann, F-35170, Bruz, Brittany.

5. HIGH AVERAGE POWER BLUE GENERATION FROM A COPPER VAPOUR LASER PUMPED TITANIUM SAPPHIRE LASER
D.W. Coutts, W.J. Wadsworth, C.E. Webb, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU.

6. RED, GREEN AND BLUE INTRA-CAVITY DOUBLED MICROCHIP LASERS
R.S. Conroy, A.J. Kemp, G.J. Friel, N. MacKinnon*, D.G. Matthews#, B.D. Sinclair, J.F. Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, KY16 9SS.
*Currently with Uniphase Lasers Corp, California, USA.
#Currently with Light Solutions Corp, Mountain View, California, USA.

16.00 TEA

POSTER PAPERS I : OPTICAL PHYSICS

1. MICROWAVE INDUCED QUANTUM JUMPS IN A SQUID RING
R. Whiteman, J. Diggins, V. Schollmann, R.J. Prance, H. Prance, J.F. Ralph and T.D. Clark, Physical Electronics Group, School of Engineering, Brighton, Sussex, BN1 9QT, UK.

2. QUANTUM OPTICS OF LOSSY BEAM SPLITTERS
Stephen M. Barnett, John Jeffers and Alessandra Gatti, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG.

3. BLACK-BODY RADIATION DESTROYS COHERENCE INDUCED IN THE MICROMASER CAVITY FIELD
A.M. Kremid and R.K. Bullough, Department of Mathematics, UMIST, PO Box 88, Manchester, M60 1QD.

4. SIMULATIONS FOR TEACHING ADVANCED LASER PHYSICS
M.H. Dunn, A.D. Gillies, P. Lindsay, B.D. Sinclair, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, Scotland, KY16 9SS, UK.

5. TOPOLOGICAL FEATURES OF A TRAPPED COLD ION
C. Baxter, R. Loudon, Department of Physics, University of Essex, Colchester, CO4 3SQ.

6. INVESTIGATION INTO PHOTOSTIMULATED LUMINESCENCE IN $BaFBr:Eu^{2+}$
D.A. Andrews*, M. Bradford*, A. Harrison#, S.G. Roden$ and T.A. King*,
* Laser Photonics, Department of Physics and Astronomy, Manchester University, Manchester, M13 9PL, UK.
# Department of Chemistry, The University of Edinburgh, The Kings Buildings, Edinburgh, EH9 3JJ, UK.
$ Company Research Laboratory, BNFL, Springfields, Salwick, Preston, PR4 OXJ, UK.

7 .CO-EXISTING CONSERVATIVE AND DISSIPATIVE BEHAVIOURS IN A COUPLED LASER MODEL
David H. Henderson and Gian-Luca Oppo, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG.

8. GIANT EXCITONIC POLARIZATION ROTATION IN LINEAR REFLECTION FROM ZnSe
G. Mohs, M. Shirane, R. Shimano and M. Kuwata-Gonokami, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113, Japan.
Yu.P. Svirko and N.I. Zheludev, Department of Physics, University of Southampton, SO17 1BJ, UK.

9. GYROTROPIC LINEAR DICHROISM AND BROKEN REVERSALITY OF LIGHT-MATTER INTERACTIONS
P.J. Bennett, S. Dhanjal, Yu.P. Svirko, and N.I. Zheludev, Department of Physics, University of Southampton, Southampton, SO17 1BJ.

10 CUBIC OPTICAL NONLINEARITIES OF METALS IN THE VICINITY OF THE MELTING POINT
P.J. Bennett, S. Dhanjal, Yu.P. Svirko and N.I. Zheludev, Department of Physics, University of Southampton, Southampton, SO17 1BJ.

POSTER PAPERS II : MICROCAVITIES AND PHOTONIC BANDGAPS

1. EXPERIMENTAL CHARACTERISATION OF EFFICIENT POROUS SILICON LIGHT EMITTING STRUCTURES DESIGNED USING A PHOTONIC BAND GAP APPROACH
P.A. Snow, E.K. Squire and P. St. J. Russell, Optoelectronics Group, School of Physics, University of Bath, Bath, BA2 7AY.

2. NOVEL PHOTONIC CRYSTALS FOR THE MICROWAVE REGIME
C.Brewitt-Taylor*, P. Dimond*, G. Fixter#, A. Laight#, P. Lederer*, P.J. Roberts*, T.J. Shepherd*, P.R. Tapster*, I. Youngs#
* DERA, Malvern, St. Andrews Road, Malvern, Worcs. W14 3PS.

SMC, DERA, Farnborough, GU14 6TD.

3. MULTIPLE QUANTUM-WELL BINARY-PHASE MODULATORS: GENERAL DISCUSSION
E. Serrano*, M.P.Y. Dsmulliez#, H. Inbar*, B.S. Wherrett*
* Department of Physics, # Department of Computing and Electrical Engineering, Heriot-Watt University, Edinburgh EH14 4
4. SPONTANEOUS EMISSION CONTROL IN EDGE EMITTING QUANTUM WELL LASER DIODES
G.W. Lewis, G.M. Berry, H.D. Summers, P. Blood, Department of Physics and Astronomy, University of Wales, College of Cardiff, PO Box 913, Cardiff, CF2 3YB. J.S. Roberts, Department of Electronic Engineering and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3DJ.

5. GUIDED MODES IN A PHOTONIC CRYSTAL FIBRE
J.C. Knight, T.A. Birks, P.St.J. Russell, School of Physics, University of Bath, Bath, BA2 7AY.
J.P. de Sandro, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ.

6. PHASE-MATCHED EXCITATION OF WHISPERING GALLERY MODES IN MICROSPHERES USING A FIBRE TAPER
J.C. Knight, T.A. Birks, G. Cheung, F. Jacques, School of Physics, University of Bath, Bath, BA2 7AY.

7. MACROSCOPIC QUANTIZATION IN QUANTUM OPTICS AND CAVITY QUANTUM ELECTRODYNAMICS: INTERATOMIC INTERACTIONS
B.J. Dalton [1] and M. Babiker [2]
[1] Physics Department, The University of Queensland, Brisbane, Queensland 4072, Australia.
[2] Physics Department, University of Essex, Colchester, CO4 3SQ, UK.

8. SPONTANEOUS DECAY IN METAL/VACUUM PHOTONIC MICROSTRUCTURES
M. Babiker, S.Al-Awfi, N. Enfati and J. Kirk, Department of Physics, University of Essex, Colchester, CO4 3SQ, UK.

9. MODIFICATION OF SPONTANEOUS EMISSION BY DIELECTRIC MEDIA
RK Bullough, Dept of Maths, UMIST, PO Box 88, Manchester, M60 1QD and F Hynne, Kemisk Institute, Universitetsparken 5. Kobenhavn 0 Denmark.

POSTER PAPERS III : QUANTUM WELL DEVICES

1. SPATIAL SOLITON PIXELS IN SEMICONDUCTOR DEVICES
A. Lord[1], W.J. Firth[1], M. Brambilla[2], L.A. Lugiato[2], F. Prati[2], and L. Spinelli[1],
[1] Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, Scotland.
[2] INFM, Dipartimento di Fisica dell' Universita di Milano, via Celoria 16, 20133 Milan, Italy.

2. ELECTRON SPIN RELAXATION IN InGaAs/InGaAsP MULTIPLE QUANTUM WELLS
J. Hyland, G.T. Kennedy and A. Miller, J.F. Allen Research Laboratories, Department of Physics and Astronomy, University of St. Andrews, Fife, Scotland, KY16 9SS.

3. GAIN MECHANISMS IN ZnSe/(Zn, Cd)Se MULTIPLE QUANTUM WELLS
C. Higgs, I. Galbraith, A.K. Kar and B.S. Wherrett, Physics Department, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK.

4. MULTIPLE QUANTUM WELL BINARY PHASE MODULATOR
L.C. Wilkinson, S.M. Prince, M.P.Y. Desmulliez*, Department of Physics, (*Department of Computing and Electrical Engineering), Heriot-Watt University, Edinburgh, EH14 4AS, Scotland.

5. QUANTIFYING INTERMIXING OF GaAs/A1GaAs QUANTUM CONFINED HETEROSTRUCTURES THROUGH KINETICS OF DEFECT DIFFUSION
A. Saher Helmy, J.S. Aitchison, and J.H. Marsh, Department of Electronics and Electrical Engineering, University of Glasgo Glasgow, G12 8QQ, Scotland, UK.

6. EXPERIMENTAL INVESTIGATIONS OF MQW InGaAs ON CMOS SMART PIXELS FOR OPTICALLY CONNECTED COMPUTERS
T. Yang, D.A. Baillie, J. Gourlay, M. Forbes, J.A.B. Dines, A.C. Walker, F. Pottier*, C.R. Stanley*, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK.
* Department of Electronics and Electrical Engineering, University of Glasgow

POSTER PAPERS IV : SEMICONDUCTOR LASERS

1. CONTROLLING CHAOTIC DYNAMICS IN EXTERNAL CAVITY LASER DIODES USING IMPULSIVE DELAYED FEEDBACK
A.V. Naumenko, N.A. Loiko and S.I. Turovets, Institute of Physics, Academy of Sciences, 70 Skarina Avenue, Minsk 22007 Belarus. P.S. Spencer and K.A. Shore, School of Electronic Engineering and Computer Systems, University of Wales, Bango LL57 1UT, Wales, UK.

2. STRONG OPTICAL FEEDBACK EFFECTS ON THE DYNAMICS OF MULTI- LONGITUDINAL MODE LASER DIODES
P.S. Spencer and K.A. Shore, School of Electronic Engineering and Computer Systems, University of Wales, Bangor, LL57 1UT, Wales, UK.

3. PUMP/PROBE DEPLETION EFFECTS ON MULTI-WAVE MIXING IN SEMICONDUCTOR LASERS
J.M. Tang and K.A. Shore, School of Electronic Engineering and Computer Systems, University of Wales, Bangor, LL57 1UT, Wales, UK.

4. MODELLING PULSE PROPAGATION IN SEMICONDUCTOR OPTICAL AMPLIFIERS USING WAVELETS
I. Pierce and K.A. Shore, School of Electronic Engineering and Computer Systems, University of Wales, Bangor, LL57 1UT, Wales, UK.

5. NORMAL INCIDENCE OPERATION IN N-TYPE UNIPOLAR OPTOELECTONIC DEVICES: THE INTERSUBBAND MATRIX ELEMENTS
W. Batty and K.A. Shore, School of Electronic Engineering and Computer Systems, University of Wales, Bangor, LL57 1UT.

6. OPERATION OF A MULTIPLE COLLIDING PULSE MODELOCKED SEMICONDUCTOR LASER AT 1.55μm
S.D. McDougall, C.N. Ironside, and C.C. Button*, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow, G12 8LT, UK.

7. EFFECT OF INHOMOGENEITY ON QUANTUM WELL FAR-INFRARED LASERS
Zhi-Jun Xin and H.N. Rutt, Department of Electronics and Computer Science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK.

8. OPTICAL FEEDBACK SUSTAINED SELF-PULSATIONS IN SEMICONDUCTOR LASERS
M. Milani, Dip. di Scienza dei Materiali, Universita di Milano, via Emanueli 15, 20126 Milano.
P. Abbati, F. Previdi, Dip. di Elettronica e Informazione, Politecnico di Milano, via G. Ponzio 34/5, 20133 Milano.

9. TECHNIQUES FOR MINIMISING IVA LOSS IN InGaSb/InA1Sb/InSb QUANTUMWELL LASERS
Mark Carroll, S. Dewar, P. Blood#, T. Ashley, C. Elliott*, (# Department of Physics and Astronomy, University of Wales Ca Cardiff, CF2 3YB. * DERA, St. Andrews Road, Malvern, WR4 3PS)

10 SELF-CONSISTENT ANALYSIS OF THE DIRECT CURRENT MODULATION RESPONSE OF UNIPOLAR SEMICONDUCTOR LASERS
C.Y.L.Cheung and K.A.Shore, University of Wales, Bangor, School of Electronic Engineering & Computer Systems, BANGOR LL57 1UT

11. QUANTUM NOISE IN SEMICONDUCTOR MICROLASERS
G.P. Barra and P. Debernadi, Torino, Italy.

POSTER PAPERS V: SOLITONS AND PATTERNS

1. NONPARAXIAL SOLITONS
P. Chamorro-Posada *, G.S. Macdonald and G.H.C. New, Laser Optics and Spectroscopy Group, The Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London, SW7 2BZ, UK. * Permanent address: Dpto. Ingenieria de Sistemas y Automatica, E.T.S.I. Telecomunicacion, C./Real de Burgos s/n, 47011 Valladolid, Spain.

2. DOUGHNUT SOLITONS IN QUADRATIC NONLINEAR MEDIA AND THEIR FRAGMENTATION
W.J. Firth and D.V. Skryabin, Department of Physics and Applied Physics, John Anderson Building, University of Strathclyde, 107, Rottenrow, Glasgow, G4 ONG, UK.

3. THEORY OF MIXED-MODE SPATIAL SOLITONS IN ANISOTROPIC CUBIC MEDIA
D.C. Hutchings, J.M. Arnold and J.S. Aitchison, Dept. of Electronics and Electrical Eng., University of Glasgow, Glasgow, G12 8QQ, UK

4. SPATIO-TEMPORAL OSCILLATIONS IN NANOSECOND OPTICAL PARAMETRIC OSCILLATORS
S.C. Lyons, G.-L. Oppo, W.J. Firth, and J.R.M. Barr*, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, Scotland.
* Permanent address: Laser Group, Pilkington Optronics, Glasgow, G51 4BZ, Scotland.

5. EFFECT OF SQUEEZING ON QUANTUM IMAGES
John Jeffers, Gian-Luca Oppo and Stephen M. Barnett, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, UK.

6. DOUBLE SQUEEZE: COMPRESSION IN BOTH SPACE AND TIME IN A KERR LENS MODE-LOCKED LASER MODEL
A.M. Dunlop and W.J. Firth, Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 ONG, U
E.M. Wright, Optical Sciences Center, University of Arizona, Tucson, AZ85721, USA.

POSTER PAPERS VI : WAVEGUIDE STRUCTURES

1. PROPAGATION OF FREQUENCY-DOUBLED LAGUERRE-GAUSSIAN BEAMS AND ROLE OF THE ORBITAL ANGULAR MOMENTUM
J.K. Courtial, K. Dholakia, L. Allen, M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, St. Andrews, KY16 9SS, UK.

2. THE TRANSFER OF ORBITAL ANGULAR MOMENTUM TO A LIGHT BEAM USING A STRESSED FIBRE OPTIC WAVEGUIDE
D. McGloin, N.B. Simpson and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, St. Andrews, KY16 9SS, UK.

3. TRANSFER OF ORBITAL ANGULAR MOMENTUM TO MICROSCOPIC PARTICLES SUSPENDED IN AN ION TRAP
J.K. Courtial, L. Allen, M.J. Padgett and K. Dholakia, School of Physics and Astronomy, University of St. Andrews, St. Andrews, KY16 9SS, UK.

4. GENERATION OF HIGHER-ORDER LAGUERRE BEAMS WITH HIGH EFFICIENCY COMPUTER GENERATED HOLOGRAMS
J. Arlt, K. Dholakia, L. Allen and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, St. Andrews. KY16 9SS, UK.

5. HYBRID WAVEGUIDE-UNSTABLE RESONATOR FOR Nd:YAG PLANAR WAVEGUIDE
A.A. Chesworth, D. Pelaez-Millas, H.J. Baker and D.R. Hall, Department of Physics, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK.

6. HIGH NUMERICAL APERTURE PLANAR WAVEGUIDES
C.L. Bonner, D.P. Shepherd, C.T.A. Brown, A.A. Anderson*, T.J. Warburton, A.C. Tropper, R.W. Eason, and D.C. Hanna, Optoelectronics Research Centre and Physics Department* University of Southampton, Highfield, Southampton, UK.

7. OPTICAL PROPERTIES AND LOCAL STRUCTURES OF GALLIUM LANTHANUM SULPHIDE/OXIDE THIN FILM FOR WAVEGUIDE LASERS
R. Asal and H.N. Rutt, Infrared Science and Technology, Department of Electronics and Computer Science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK.

8. QUASI-MODES OF PERIODIC SEGMENTED WAVEGUIDES
D. Ortega, J.M. Aldariz, J.M. Arnold and J.S. Aitchison, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow, G12 8QQ.

9. CONFINING ELECTRONS AND PHOTONS
E. Dix, J.E. Inglesfield and S. Dewar, Dept. of Physics and Astronomy, University of Wales Cardiff, PO Box 913, Cardiff, CF2 3YB. J. Heaton, DERA, Malvern, Worcs. WR14 3PS.

POSTER PAPERS VII : APPLICATIONS

1. A NEW METHOD FOR HIGH SPEED IMAGING OF PARTICLES WITHIN INTENSELY RADIATING PLASMAS
F.B.J. Buchkremer, A.J. Andrews, D.W, Coutts and C.E. Webb, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.

2. PARTICLE CHARACTERISATION FROM FLUCTUATIONS IN POLARISED RADIATION
A.P. Bates, K.I. Hopcraft, Department of Theoretical Mechanics, University of Nottingham, NG7 2RD, UK.
E. Jakeman, Dept. Electrical and Electronic Engineering, University of Nottingham, NG7 2RD, UK.

3. DIFFRACTIVE PHASE ELEMENTS FOR HIGH-EFFICIENCY PATTERN FORMATION TASKS
I.M. Barton, P. Blair, A.J. Waddie and M.R. Taghizadeh, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK.

4. HIGH-EFFICIENCY DETECTION OF SINGLE PHOTONS AT PICOSECOND RESOLUTION FOR USE AT TELECOMMUNICATION WAVELENGTHS
Gerard S. Buller, Philip A. Hiskett, Stuart J. Fancey, Ivair Gontijo, Paul D. Townsend, *
Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, UK (* BT Laboratories, Martlesham Heath, Ipswich, IP5 7RE)

5. THE MEASUREMENT OF THE WAVEFRONT QUALITY OF THE VULCAN LASER SYSTEM - ADAPTIVE OPTIC POSSIBILITIES
J. Collier, D.A. Pepler, C.N. Danson, I.N. Ross, C.B. Edwards, P. Exley, T.B. Winstone, J. Elwood, D. Hitchcock, Central Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 OQX, UK.

6. PHOTOSENSITIVITY IN PHOSPHOSILICATE GLASSES CODOPED WITH TIN PRODUCED BY FLAME HYDROLYSIS DEPOSITION AND AEROSOL DOPING
P.V.S. Marques[a, b], J.R. Bonar[a], A. McLaughlin[a], A.M.P. Leite[b], J.S. Aitchison[a]
a) Dept. of Electronics and Electrical Engineering, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK.
b) Centro de Fisica do Porto, Rua do Campo Alegre, 687 4150 Porto, Portugal.

7. AN INFRARED FOURIER-TRANSFORM SPECTROMETER BASED ON WOLLASTON PRISMS
D. Steers, W. Sibbett and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, KY16 9SS.

8. AN ULTRA-COMPACT STATIC FOURIER-TRANSFORM SPECTROMETER USED AS A LASER WAVEMETER
D. Steers, B.A. Patterson, W. Sibbett and M.J. Padgett, School of Physics and Astronomy, University of St. Andrews, KY16

9. IMPLEMENTATION OF THE *OPTICAL HIGHWAYS* GENERAL PURPOSE PARALLEL COMPUTER INTERCONNECT SCHEME
Julian A.B. Dines and John F. Snowdon, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, UK.

POSTER SESSION VIII : SOLID STATE AND FIBRE LASERS

1. ULTRALOW-THRESHOLD KLM Cr^{3+}:$LiSrFaF_6$ LASER PUMPED BY A SELF- INJECTION-LOCKED A1GaInP DIODE LASER
P. Loza-Alvarez, J-M. Hopkins, G.J. Valentine, D. Burns and W. Sibbett, J.F. Allen Research Laboratories, School of Physic and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, Scotland, KY16 9SS, UK.

2. A CONTINUOUS-WAVE SINGLY-RESONANT INTRACAVITY OPTICAL PARAMETRIC OSCILLATOR BASED ON PPL
G.A. Turnbull, T.J. Edwards, M.H. Dunn and M. Ebrahimzadeh, School of Physics and Astronomy, University of St. Andrews St. Andrews, Fife, KY16 9SS, Scotland.

3. STEADY-STATE AND TRANSIENT ANALYSIS FOR CONTINUOUS-WAVE INTRACAVITY SINGLY-RESONANT PARAMETRIC OSCILLATORS
G.A. Turnbull, M. Ebrahimzadeh and M.H. Dunn, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, KY16 9SS, Scotland.

4. HIGH POWER DIODE BAR PUMPED Tm:YAG LASER AND INTRACAVITY PUMPED Ho: YAG LASER
R.A. Hayward, C. Bollig, W.A. Clarkson and D.C.Hanna, Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK.

5. FEMTOSECOND-PULSE GENERATION FROM A Cr^{3+}:$LiSrAlF_6$ LASER PUMPED BY A LOW-POWER SINGLE-STRIPE A1GaInP DIODE LASER
J-M. Hopkins, P. Loza-Alvarez, G.J. Valentine, D. Burns and W. Sibbett, J.F. Allen Research Laboratories, School of Physic and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, Scotland, KY16 9SS, UK.

6. HIGH EFFICIENCY SECOND HARMONIC AND SUM FREQUENCY GENERATION OF NANOSECOND PULSES IN A CASCADED ERBIUM DOPED FIBRE:PPLN SOURCE
D. Taverner, P. Britton, P.G.R. Smith, D.J. Richardson, G.W. Ross and D.C. Hanna, Optoelectronics Research Centre,

University of Southampton, Southampton, SO17 1BJ, UK>

7. POLARIZATION EIGENMODES OF A Nd:YVO_4/KTP INTRACAVITY FREQUENCY-DOUBLED MICROCHIP LASER
A.J. Kemp, R.S. Conroy, G.J. Friel, B.D. Sinclair, J.F. Allen Physics Research Laboratories, School of Physics and Astronom University of St. Andrews, St. Andrews, Fife, KY16 9SS, Scotland.

8. HIGH-POWER BLUE LIGHT GENERATION IN PERIODICALLY-POLED LITHIUM NIOBATE
G.W. Ross, M. Pollnau, P.G.R. Smith, P.E. Britton, W.A. Clarkson, D.C. Hanna, Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ.

9. PASSIVE Q-SWITCHING OF ND:YVO_4 MICROCHIP LASERS
R.S. Conroy, E.A. Marks, A.J. Kemp, G.J. Friel, B.D. Sinclair, J.F. Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, Scotland, KY16 9SS, UK.

10.POLARISATION CONTROL IN TOP-SURFACE EMITTING VERTICAL CAVITY LASERS BY POST PROCESSING USING FOCUSED ION BEAM ETCHING

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QE13 : WORKSHOP ON MICROCAVITIES AND PHOTONIC BANDGAPS

1400-1800 Wednesday 10 September 1997
General Approach

It is wished to encourage a lively discussion of hot topics within the scope of the workshop. Lead speakers are expected to set the scene for discussion and then the meeting will be open for short contributions from all participants. It is hoped that contributors will be prepared to be speculative if not provocative. Presentations of work-in-progress are especially seen to be within the spirit of the workshop format.

It is anticipated that authors of papers scheduled for presentation in Poster Section II : MICROCAVITIES AND PHOTONIC BANDGAPS will be particularly keen to make a contribution to the Workshop. It is emphasised, however, that contributions are NOT restricted to those authors.

It would be helpful if indicationsof intention to contribute could be made to the appropriate Workshop session chair - at least by the start of the session . This will allow the chair to ensure as much participation as possible in the workshop. Additional contributions stimulated by presentation in the workshop will, of course, also be greatly appreciated.

1400 SESSION A : MICROCAVITIES

Chair Dr Paul Rees, University of Wales, Bangor

Lead speakers : G. Parry, University of Oxford ; J.Hegarty, Trinity College, Dublin.

1440 Short Contributions (Typically 5 minutes) and Discussion.

1530 Tea

1600 SESSION B : PHOTONIC BANDGAPS
Chair Dr Susan Dewar, University of Wales, Cardiff

Lead speakers: R de la Rue, University of Glasgow; P.Russel, University of Bath.

1640 Short Contributions (Typically 5 minutes) and Discussions.

1730 Workshop Summary

1800 Close

CONTENTS

ORAL SESSIONS

INVITED SPEAKERS

A BIOLOGICAL MICROCAVITY LASER

Paul Gourley

Using GaAs surface-emitting lasers, scientists at Sandia National Laboratories in Albuquerque, NM have demonstrated a revolutionary new method for analysing biological cells. The method employs a semiconductor laser with human cell acting as an internal component of the laser. The cell actually aids the light-generating process, so the emitted laser beam is impressed with information about the cell. The new 'biological microcavity laser' provides the basis for new biomedical analysis of cell structure. This includes both living and fixed cells from humans, animals and plants. And the technique doesn't require the customary chemical staining procedure to render it's structure visible. Further, the cells can be connected in tissues, so long as the tissue is thinned to monolayer dimensions to fit within the laser cavity. Thus, the laser has potential uses for a novel kind of microelectronic cytometry and histopathology.

This intracavity laser technique provides coherent light spectra and images of cells and intracellular structures and has several critical advantages over conventional cell analysis methods. In preliminary experiments, the laser has shown potential to probe the human immune system (caliper cell and nucleus dimensions of lymphocytes, characterise genetic disorders (quantify sickle and normal red blood cell shapes, shown in Fig. 1), and distinguish cancerous and normal cells from tumours. It may be useful for pharmaceutical development by high-speed drug testing of living cells, or finding rare cells in large populations.

Resonant Cavity Light Emitting Diodes

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The generic structure of a resonant cavity light emitting diode consists of light generating quantum wells located inside an optical cavity defined by two reflectors. Usually one of the reflectors is a distributed Bragg reflector whose reflectivity is determined by the number of periods it comprises and the other is a high reflectivity metal mirror. Apart from the metal mirror, the entire structure is formed by epitaxial growth of semiconductor layers so the optical cavity is usually only a micron or so in length. Typically, the structure will contain 3 quantum wells located at an antinode of the electric field in the structure and the number of periods in the Bragg structure can vary from 2 to 16. The structure clearly resembles the vertical cavity surface emitting laser but the reflectivities of the mirrors are not high enough to allow lasing action and spontaneous emission dominates.

The devices are interesting because the micro-cavity influences the optical linewidth, peak spectral power density and angular distribution of the emitted radiation. Changes in these factors might be expected on simple physical arguments but there are often subtleties which are less obvious but significant. The observed enhancement of the efficiency was probably not anticipated but it is this factor which is perhaps the most interesting. The efficiency of conventional LEDs is dependent on carrier injection efficiency, internal quantum efficiency and extraction efficiency, that is the fraction of light which can be transmitted through the semiconductor surface. The high refractive index (3-3.5) of the semiconductor material prevents most of the light leaving the material, instead reflecting it back by total internal reflection at the air-semiconductor interface, hence limiting the extraction efficiency of the device. The resonant cavity modifies the angular distribution of emission in such a way that a much larger fraction of the emitted light falls within the critical cone angle and is able to leave the device, thus substantially enhancing the device efficiency.

We will review the development of the microcavity LED showing results on InGaAs/GaAs quantum well devices emitting at around 960nm and some recent results on InAsP quantum wells emitting at around 1350nm. Evidence of linewidth narrowing, enhanced peak powers emission and efficency (at 960nm) will be presented. Recent results on high speed switching will also be presented and designs offering possible further enhancements in switching speed will be discussed.

1. Laser Dynamics

NOVEL Q-SWITCHING OF A MICROCHIP LASER USING A QUADRAPOLE DEFLECTOR

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Microchip lasers are typically formed by applying dielectric mirrors directly to two near-parallel surfaces of a thin slice of laser gain material. $Nd:YVO_4$ is a commonly used gain material because of its short absorption depth and high stimulated emission cross section. If a discrete output coupler is used, an electro-optic Q-switch may be used to produce short pulses in a compact design.

Ireland and Ley showed deflection could be achieved in a single-crystal gradient deflector, and proposed that this could be used as a Q-switch [1]. To our knowledge this has not yet been attempted. A 2x2x25mm $LiTaO_3$ crystal was fabricated as a quadrupole deflector and coated with anti-reflection coatings for use as a Q-switch in a $Nd:YVO_4$ microchip cavity. The insertion loss for the Q-switch was found to be 2%, though with optimised coatings this potentially could be much lower.

A transistor chain, producing a voltage of 600V, was used to cause the deflection, with a switching time of 23ns and a rise time of 100μs. The maximum repetition speed was limited to 10kHz by the drive electronics, though this is sufficient to make good use of the 110μs upper state lifetime of 1% $Nd:YVO_4$.

A 3x3x1mm crystal of $Nd:YVO_4$ was used as the gain crystal and coated HR/AR at 1064nm. A selection of output couplers, forming a 40mm long cavity, were investigated to show the performance of the Q-switch. The optimum output coupling was found to be approximately 75% yielding 7.9ns pulses with a peak power of 1.65kW at 4kHz. At 1kHz, the Q-switch was found to give shorter pulses of 7.4ns and a peak power of 1.9kW. These pulse energies are similar to those obtained by Zayhowski for a variable length etalon used to Q-switch a Nd:YAG microchip, and with faster switching times should yield similar peak powers, without the same constraints on power scaling of the system [2]. The maximum CW power obtained was 53mW giving a slope efficiency of 11%. The slope efficiency of the laser without the voltage applied is 46% and 47% without the Q-switch in the cavity.

We believe this to be the first demonstration of a deflective Q-switch used to modulate the output of a miniature laser. With optimisation of the gain material and switching technique, shorter pulses with higher peak powers should be possible.

This work was supported in part by the EPSRC and DTI on the LINK Project ELVIS. The project collaborators are: GEC-Marconi Ltd, Leysop Ltd, Tritech International Ltd and St.Andrews University.

[1] Electro-Optic and Acousto-Optic Scanning and Deflection, Gottlieb M, Ireland C L M, Ley J M, Marcel Dekker Inc, Chapter 4
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A HIGH POWER Q-SWITCHED ERBIUM FIBRE LASER PRODUCING 50μJ PULSES

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Q-switched fibre lasers have been extensively researched since the first development in 1986 [1]. Recent numerical modeling [2] has suggested that two methods can be used to improve the energy storage per unit length within a fibre. One technique is to increase the Erbium concentration which will however, lead to clustering of Erbium ions which decreases the efficiency of the fibre through co-operative up-conversion. The method which we will present is based on using a novel fibre geometry using a large mode field area. Single-mode operation is maintained by decreasing the N.A. of the fibre.

The setup for the experiment is as shown in Figure 1. An Argon pumped Ti-Sapphire laser provides a pump source of up to 600mW at 980nm through the fibre. To prevent unwanted lasing from 4% Fresnel relection, the far end of the fibre was angle polished at 16%. The optimised length of the fibre was 60cms. Due to the low diffraction efficiency of the acousto-optic modulator (AOM), the optimum results were obtained though zero order operation.

Using this configuration, peak powers in excess of 4kW with corresponding pulse widths of 11ns were obtained at a repetition rate below 1kHz. The variation of peak powers and pulse widths with repetition rate will be shown to be typical for that of a Q-switched Erbium laser. At high pump powers, the increase in pulse energy was saturated due to the increase of ASE power, clamping the available gain. For an input pump power of 600mW, the output pulse energy was 50μJ.

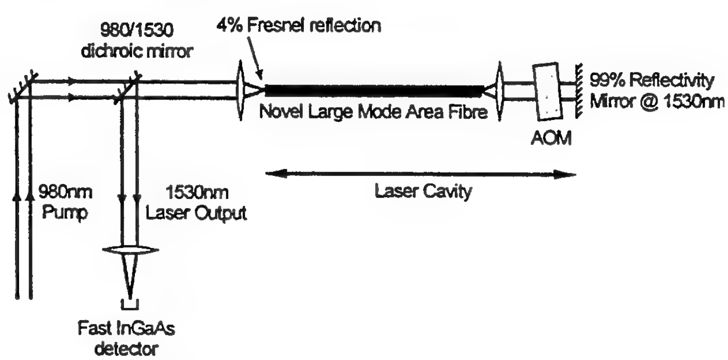

Figure 1: Experimental setup for the Q-switched laser

[1] R.J.Mears, L.Reekie, S.B.Poole, D.N.Payne: Electronics Letters **22**, 159 (1986)
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EXPERIMENTAL AND THEORETICAL BEHAVIOUR OF ALL-SOLID-STATE KERR-LENS MODE-LOCKED LASERS

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All-solid state Kerr-Lens Mode-Locked Cr:LiSAF oscillators have been developed and their performance compared with the predictions of computational models. Both three- and four-mirror cavity configurations have been studied, and particular attention paid to effects associated with the spatial gain profile. The theoretical results are presented as design maps intended for laboratory use.

While diode-pumped solid-state lasers generating ultrashort pulses by the process of Kerr-Lens Mode-Locking (KLM) have enormous potential in real-world applications, the design of KLM lasers still involves a significant empirical element. KLM is the most complicated mode-locking process in common use. This is because the process relies on changes to the global cavity mode profile which is both influenced by *and itself influences* the spatial gain profile in the laser rod. At the same time, changes in the mode profile within the rod impact on the Kerr-lensing process itself. The delicate interplay of these competing processes makes for a highly complex nonlinear problem, especially for diode pumping where the pumping profile is very non-uniform Our theoretical analysis employs two parallel models, the first based on an extension [1] of the semi-analytical approach of Magni *et al.* [2], and the second on a beam propagation code. Results from the numerical method are used to check and refine the predictions of the simpler approach which generates the design maps. Both models include astigmatism, nonlinear coupling between orthogonal polarisations, arbitrarily non-uniform pumping, gain-guiding, gain-aperturing, and gain saturation.

The theoretical models have been applied to our conventional four-mirror diode-pumped Cr:LiSAF laser which has generated pulses as short as 24 fs [3]. More recently, we have demonstrated self-starting femtosecond KLM operation in diode-pumped Cr:LiSAF and Cr:YAG lasers with compact *three*-mirror cavities [3-4]; these systems, in which gain-aperturing is the principle mode-locking mechanism, are considerably easier to align that their four-mirror counterparts, and will hopefully provide robust operation with useful output powers using low-cost broad-stripe pump diodes.

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COMPRESSED 200FSEC PULSES FROM A SYNCHRONOUSLY PUMPED OPTICAL PARAMETRIC OSCILLATOR IN PERIODICALLY-POLED LITHIUM NIOBATE

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A cw synchronously-pumped optical parametric oscillator (SPOPO) based on periodically-poled lithium niobate (PPLN) has produced a factor of 20 pulse compression, resulting in signal pulses as short as 200fs, when driven by 4ps pump pulses. Furthermore these compressed pulses extract most of the energy from the pump pulses so that the output signal pulses have higher peak power than the pump pulses.

The principle of this pulse compression in a SPOPO has previously been demonstrated in BBO, using very intense (~1MW) Q-switched mode-locked pulse trains[1]. The requirements for pulse compression were identified as high gain (10^2-10^3 quoted in[1]) and large group-velocity walk-off between pump and resonated wave. Thus when the OPO resonator is biassed longer than the length for exact synchronism, the resonated signal pulse arrives at the nonlinear crystal late relative to the pump pulse and then 'walks-through' the pump pulse over the crystal length. The high gain allows the leading edge of the signal pulse to deplete the entire pump pulse so that essentially all of the pump pulse energy is extracted into the compressed pulse.

We have shown that this principle can be extended to the case of cw mode-locking in PPLN, since high gains can be achieved for much lower pump powers. In fact we also find that the required gain in the cw mode locked case is only ~10.

In the first experiment on a 1047nm pumped PPLN OPO[2], we used a 6mm sample that we had fabricated by electric-field poling. For these compression experiments we used a longer crystal (19mm, fabricated by Crystal Technology). The length was chosen to provide a group delay between pump and signal which was comparable to the 4ps pump pulse duration. A 4 mirror OPO resonator was used, either as a standing wave resonator or as a ring. The output mirror was an uncoated flat of $LiNbO_3$ or ZnSe, providing a 15% reflectivity, hence forcing operation in the high-gain regime. The OPO was pumped by a diode-pumped Nd:YLF mode-locked laser (4psec, 120MHz, mean power ~1W, Microlase DPM-1000-120). With the resonator set for exact synchronism, the signal pulses (tunable over 1.7-1.9μm) were 4psec in duration and the average power ~300mW. With the resonator length increased by ~50μm, compressed pulses of 200-250fsec were obtained at an average power of ~220mW. These compressed pulses were extremely stable, and had a time bandwidth product of ~0.33. The idler pulses, in the 2.3 to 2.7μm range, also showed compression, although to a smaller extent.

These compression results confirm PPLN as a material well suited to ultrashort uses and offering a convenient route to broad tunability in the femtosecond regime.

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DYNAMICS OF THREE-LEVEL SYSTEMS FORMULATED FOR SEMICONDUCTORS USING SU(3) SYMMETRY

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Glasgow G12 8QQ

The SU(3) symmetry, which has previously been applied to particle and nuclear physics, is used to derive a system of 8 equations equivalent to Maxwell-Bloch equations for a three-level system.[1] These can be applied to a number of resonant nonlinear optical processes, for example, excited-state absorption, two-photon absorption and electromagnetically induced transparency. Here the appropriate form for semiconductors is derived making use of the rigourous $\mathbf{A} \cdot \mathbf{p}$ dipole interaction rather than $\mathbf{E} \cdot \mathbf{r}$. From the Fourier-transform of the dynamical equations, a recursion (perturbative) relation is obtained which is used to derive the full form of the second-order susceptibility.

Semiconductors have relatively large second-order nonlinearities (with applications for second-harmonic generation, parametric amplifiers and oscillators, optical rectification, etc.) but lack a ready means of phase-matching. It has been shown that quantum well disordering can provide the necessary spatial modulation in the second-order susceptibility.[2] Asymmetric semiconductor quantum heterostructures induce nonlinear coefficients d_{15}, d_{31} and d_{33} which have been predicted to have coefficients as large as several hundred pmV^{-1} for typical structures of dimensions of a few nanometers.[3,4] However, it is found here with the full, correct form of the nonlinear susceptibility and a nonparabolic bandstructure that there is a large degree of cancellation of the various terms and coefficients of a few pmV^{-1} are more typical for structures of this size. This is in accord with experimental observations.[5] However, it is shown that larger, more useful coefficients should be obtainable with asymmetric superlattices.

The bulk nonlinear coefficient d_{14} is also calculated for GaAs. Using the expressions calculated here, it is predicted that typical blueshifts (due to disordering) of the fundamental absorption edge can produce a substantial (absolute) modulation in this coefficient.

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PULSED SINGLE-MODE LASERS IN MULTI-MIRROR GRAZING INCIDENCE CAVITIES

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Spectroscopic applications require narrow bandwidths and in many cases single mode (SLM) laser operation is necessary. The grazing incidence cavity (GIC) is a common technique for obtaining narrow bandwidth from a laser. However, the GIC alone does not always ensure SLM operation[1] and we have found it necessary to add other mode selecting elements to the cavity. Previously, we have shown how the addition of extra mirrors to the GIC not only reduces the threshold, but also increases the mode selectivity thereby ensuring SLM operation. This increased mode selection arises from the cavity forming an interferometer that discriminates against all but one mode. We now report the demonstration of a variety of these new cavities and the development of a generic analysis of the interferometric mode selection. Figure 1 depicts one of the multi-mirror cavities; the laser medium in our experiments is Ti:Sapphire pumped by a doubled Nd:YAG. Figure 2 shows the interferometric loss modulation as a result of the extra mirror, leading to only a narrow region where oscillation is possible. Figure 3 shows the resulting single mode output from the laser.

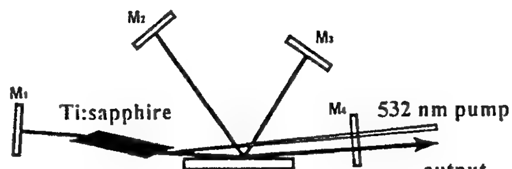

Fig 1. The multi-mirror grazing incidence cavity

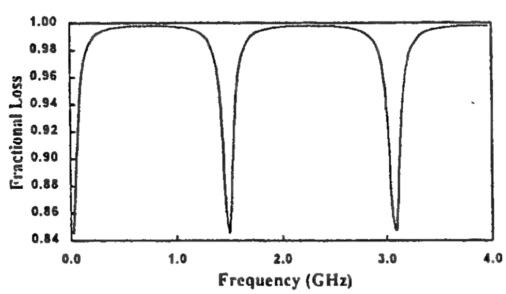

Fig 2. Interferometric loss modulation

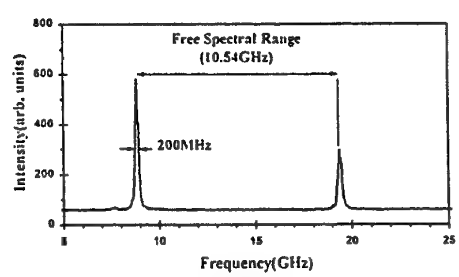

Fig 3. Etalon transmission showing single mode operation

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2. Spontaneous Emission Control

MOLECULAR FLUORESCENCE ABOVE PLANAR AND CORRUGATED METALLIC FILMS

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The decay properties of an excited dye molecule are modified by proximity to a metallic surface. Two distance regimes can be identified. For small distances, less than one tenth of the emission wavelength, the fluorescence is quenched by the metal. Coupling occurs between the near field of the molecule and surface modes , known as surface plasmon polaritons (SPPs), which propagate at the metal/dielectric interface. As a consequence, the intensity of the fluorescence and the excited state lifetime of the dye molecule are greatly reduced, figure 1. At larger distances, up to a few emission wavelengths, the decay properties are determined by the interference between direct and reflected emission. This gives rise to oscillations in the excited state lifetime of the dye molecule with distance and modifies the radiation pattern, figure 1.

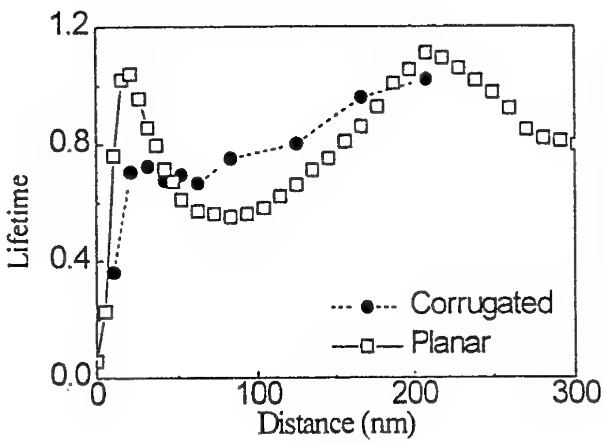

Figure 1

Corrugation of the surface leads to two interesting results. Firstly, the reflectivity of the surface is modified changing the nature of the oscillations of the excited state lifetime. Secondly, introducing a periodicity into the surface causes Bragg scattering of the SPP modes. This has two implications. Firstly, the SPPs can scatter from the periodicity to couple to radiation modes above the metal. This is of importance since the energy lost to surface modes can be recovered. This has implications for light emitting devices that contain metallic contacts or electrodes. Secondly, an energy band gap is produced in the dispersion of the SPP mode. If the gap occurs at the emission frequency of the dye molecule, quenching of the fluorescence can be significantly altered.

Excited state lifetime measurements above planar and corrugated silver films will be presented highlighting the importance of the SPP mode in determining the decay rate. The influence of corrugations in the surface profile of the metal film will be presented and discussed.

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MEASUREMENTS OF THE SPONTANEOUS EMISSION FROM SINGLE DYE MOLECULES IN A MICROCAVITY

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The realisation of a reliable source of single photons is of significant interest for both fundamental science and for applications including quantum cryptography, and quantum computing. One route towards achieving this aim is to use a single dye molecule which can only emit one photon at a time.

In this paper we report measurements of the spontaneous emission from dilute solutions of rhodamine 6G in a microcavity. When only a small number of molecules are contained within the illumination volume, the emission intensity exhibits strong fluctuations. We have measured the autocorrelation function of this signal and so simultaneously characterised the fluctuations over nine orders of magnitude of time, from nanoseconds to seconds, figure 1. The results show three characteristic times. At zero time there is a dip due to antibunching. The width of this dip, 1.56±09 ns, is related to the lifetime of the excited state. We also see a decay with a time constant of 7±2 μs which is attributed to the triplet state, and a further decay with a time constant of 2.7±0.2 ms which is consistent with the diffusion of the molecules through the pump volume. The magnitude of the effects indicate that we are operating in the single molecule regime.

The results from measuring the fluctuations over such a large range of time scales have increased our understanding of the dynamics of dye molecules in microcavities and are encouraging for the prospects of achieving a reliable source of single photons with this system.

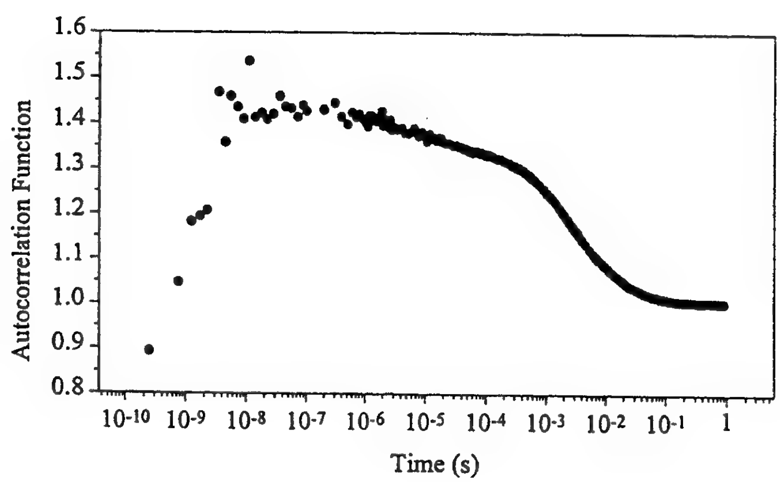

Figure 1

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MODIFICATION OF SPONTANEOUS EMISSION BY DIELECTRIC MEDIA

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Spontaneous emission is not an immutable property of an atom or molecule but can be either suppressed or enhanced by its environment. One way of achieving this is to place the atom near to a reflecting surface [1] or in a waveguide [2] so that it experiences a vacuum field modified by the change in boundary conditions. An alternative method is to embed the atom in a dielectric host [3].

We will present calculations of the spontaneous emission rates for atoms close to real dielectric surfaces taking full account of absorption and longitudinal fields associated with the medium. Our results agree with classical calculations [4] and with available experimental data [5].

Causality imposes a constraint on the allowed suppression or enhancement of spontaneous rates in the form of a sum rule [6]. We will show that the decay rate for an atom in front of a dielectric surface obeys the sum rule. However, results obtained for perfectly reflecting surfaces do not satisfy the sum rule, although they do obey a generalised form of sum rule.

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Improved Photon Number Squeezing in Light Emitting Diodes

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In this paper we report photon number squeezing measurements on high efficiency infrared light-emitting diodes.

Since the first reported reduction in the quantum noise level using light-emitting diodes in 1987 [1], the effect has been confirmed by several authors. As commercial infrared LED's have shown a marked performance improvement in recent years, an increasing noise reduction below the standard shot noise limit could be achieved. Recent measurements reported LED quantum efficiencies of >30% at low temperatures (77K) and maximum response frequencies of typically 1MHz [2].

We have investigated the noise properties of commercial transparent substrate (TS) infrared LED's consisting of a double AlGaAs heterostructure. Shot noise measurements have been performed both at room temperature and at 77K using tightly coupled large area silicon photodiodes. A quantum efficiency of >25% (at room temperature) and >40% (at 77K) has been obtained, leading to an observed noise reduction below the standard shot noise limit of 1.1dB and 2.05dB respectively. In addition, the LED's show an improved current modulation response, resulting in a cut off frequency of >10MHz.

Compared to typical performance levels of laser diodes with quantum efficiencies of about 60% and squeezing bandwidths in the GHz-range, the performance level of light-emitting diodes is still low. However an advantage of using LED's instead of laser diodes is that one avoids additional noise due to spurious optical feedback as well as partition noise due to mode competition. As the performance level of commercial LED's can be expected to improve further in the form of small junction AlGaAs heterostructures [3], the importance of LED's for the generation of light with sub-Poissonian photon statistics will increase.

In addition, we have studied the quantum correlations in series coupled high efficiency LED's. The experimental data confirms the theoretical predictions, showing a correlation coefficient of $C \approx 0.25$ at room temperature and $C \approx 0.40$ at 77K using shot noise current and virtually no correlation when running the LED's with a sub-Poissonian high-impedance current source. These enhanced correlations play an important role for quantum-non-demolition (QND) measurements with an accuracy below the standard quantum limit.

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3. Laser Applications

PROGRESS TOWARDS A LASER GUIDE STAR SYSTEM FOR USE IN ASTRONOMICAL ADAPTIVE OPTICS

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Laser guide stars (LGS) are required to provide significantly increased sky coverage, compared to natural guide stars, for astronomical telescopes incorporating adaptive optics. Resonant scattering of a high power pulsed laser from atomic sodium in the mesosphere enables the production of an artificial guide star. However, the efficient generation of a bright enough LGS using pulsed excitation is difficult due to the saturation characteristics of the mesospheric sodium. The system under development will be scaleable to provide increased average power (over 200 W) without increasing the peak power (of order 10 kW), thereby enabling the return from the sodium layer to be increased linearly with the number of laser sub-units used. The system consists of a dye master oscillator (DMO), pulsed dye amplifiers (PDA), fibre-optic delivery of the DMO and pump laser outputs and a pulse multiplexing mechanism[1].

The DMO consists of an argon ion pumped, cw dye laser (Coherent 599-21) locked using polarisation spectroscopy[2] to a hyperfine transition in the sodium D_2 line at 589 nm. Using this locking technique in a sodium vapour cell the dye laser has been locked to ±0.5 MHz for a period of over 7 hours. The spectral bandwidth of the DMO is then broadened to effectively 600 MHz using electro-optic phase modulation in order to achieve efficient excitation of the Doppler broadened sodium layer.

The PDA units are seeded by the DMO and transversely pumped by high power pulsed lasers. They have a double pass configuration in order to saturate the laser transition and achieve efficient conversion of the pump laser power. Preliminary experiments using ~200 mW cw DMO output show that two dye cells per PDA unit (a high-gain pre-amplifier and a low gain, saturated power amplifier stage) may be required to give optimum conversion efficiency.

In order to reduce the weight of the system and thermal turbulence in the telescope dome, the DMO and pump lasers will be sited remotely and the beams delivered to the dye amplifiers via optical fibres. Efficient fibre-optic delivery of single unit high power copper vapour pump lasers has been demonstrated using multimode optical fibre of various core sizes, for example, over 10 W for 100 μm fibre and over 24 W for 550 μm fibre has been achieved.

We will present detailed results of experiments on the sodium frequency lock, the pulsed dye amplifiers and the fibre-optic laser beam delivery.

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DIFFRACTIVE OPTICAL ELEMENTS FOR LASER ENGINEERING AND MATERIAL PROCESSING APPLICATIONS.

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The transformation of a laser beam power distribution into an application specific form is possible with diffractive optical elements (DOEs). In fact, complex transformations can be performed that are not possible with conventional refractive optics. By employing VLSI based fabrication processes we have produced a large number of free space DOEs for beam shaping and for the generation of large arrays of beams. In this paper we concentrate on a number of DOEs designed specifically for laser engineering and material processing applications.

The conversion of a Gaussian TEM_{00} mode into a flat top circular or rectangular intensity profile is beneficial in surface treatment, laser amplification and target illumination (e.g. in inertial confinement fusion systems). We describe the design, fabrication and experimental testing of near-field space-variant DOEs designed for wavefront transformation.

Laser scabbling of concrete, i.e. the removal of the surface layer by laser processing, is a potential tool in the decommissioning of nuclear installations. High laser powers are employed in this task, typically 3.5 kW (at a wavelength of 10.6 μm). In order to improve the efficiency of this process DOEs have been investigated that reshape the scabbling beam. We describe the design, fabrication and experimental implementation of the DOEs, with particular emphasis on the effect of the high laser power on the DOE.

A further instance of the use of DOEs to improve process efficiency is found in direct laser casting, or cladding. This is the rapid prototyping of complex mechanical parts by depositing multi-layer metallic stacks by fusing successive metallic powder tracks. In order to reduce both laser power and powder consumption and to promote a square cross section in the stack, DOEs have been designed that reshape the laser output. Again the design, fabrication and experimental implementation will be described.

A NOVEL TECHNIQUE FOR INTERFEROMETRIC SURFACE PROFILING WITHOUT FRINGE AMBIGUITY

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Optical surface profilometry is used widely throughout manufacturing and medical science. In this paper we present a novel technique for interferometric imaging of the surface profile without any ambiguities associated with fringe counting. Interferometric techniques rely on the interference between two channels within an interferometer. One channel contains the sample surface the other a reference flat or, as in our case, an adjacent part of the same sample. Using a source with a finite coherence length with orthogonally polarised interferometer channels, the surface height is found directly from the measurement of the resultant polarisation state. Six simultaneous measurements are needed to define the polarisation state of the light via Stokes parameters. Hence six interferograms are used in the algorithm which gives the surface mapping and reflectivity without any ambiguities associated with fringe counting or phase unwrapping.

A novel interferometer has been designed which is applicable for surface profilometry. Most interferometers compare the sample to a reference mirror but this poses two problems. First the system is sensitive to sub-wavelength variations in the relative position of the mirror and secondly some surfaces exhibit a complex phase/amplitude response. To this end we have developed an interferometer based on birefringent optical components which compares the sample not to a reference mirror but to an adjacent area of the same sample.

Results will be presented of both the technique as applied to date (see figure 1) and its potential for implementation of profilometry in scientific and engineering environments.

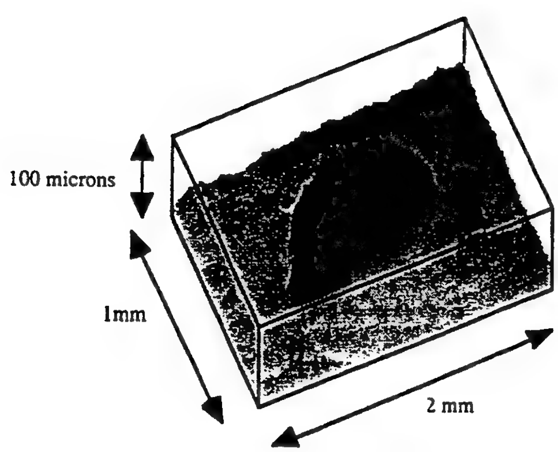

Figure 1 - Image showing experimental results for a raised surface

A novel method of increasing the range of 1.65μm OTDR using a Q-switched Erbium fibre laser

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This paper demonstrates a novel method of increasing the range of a 1.65μm optical time domain reflectometer system (OTDR). OTDR measurements at 1.65μm are more sensitive to fibre macro and micro bending losses than those produced at wavelengths 1.3 and 1.55μm. This enables problems to be identified in their early stages reducing the risk of total system failure. However, the dynamic range of current 1.65μm OTDR systems is limited by the power of the available laser diodes.

Recently we have developed a high power 1.65μm pulsed source [1]. This source was developed using a Q-switched Erbium fibre laser. The pulsed output from the fibre laser at 1.53μm generates the required pulse at 1.65μm by a process of stimulated Raman generation. Pulses of 8watts, 10ns with an optical 3db bandwidth of 25nm centered at 1.65μm are produced. These pulses are combined with a novel method of increasing the range of OTDR by using the fibre under test as an additional Raman amplification medium.

An increase in dynamic range of 17.5dB has been demonstrated by amplifying the 1.65μm signal using the 1.53μm pump within the sensing fibre. Raman amplification occurs when the 1.53μm and 1.65μm pulses overlap due to dispersion within the fibre. By delaying the pump pulse with respect to the OTDR pulse, amplification of the later may be delayed by tens of kilometres (Figure 1).

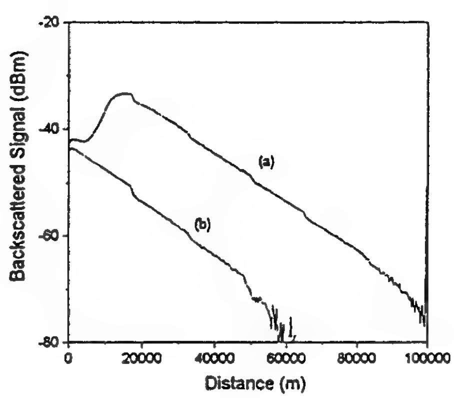

Figure 1 - Backscattered Signal with (a) and without (b) amplification

The advantage of this technique arises from the ability to operate the system with the OTDR probe pulse at a value just below the stimulated Raman threshold 10's of kilometres from the front end of the fibre.
Due to the directionality of the Raman gain, amplification is achieved without introduction of any significant noise penalty.

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A SINGLE PHOTON COUNTING TIME-OF-FLIGHT IMAGING SYSTEM

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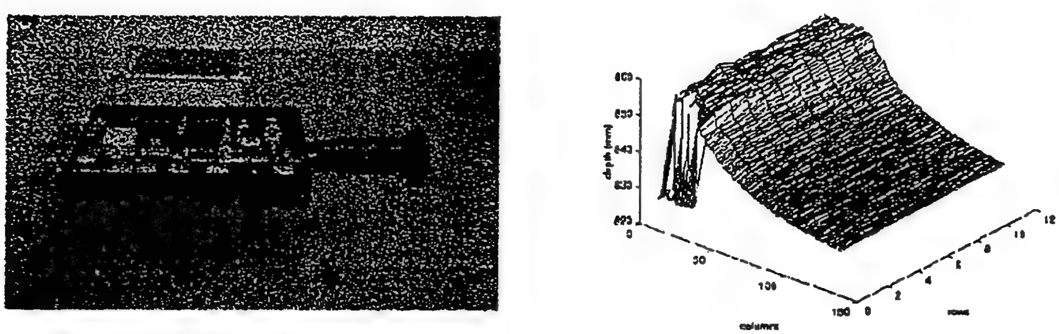
There is a requirement in the aerospace and other related industries for measuring both large (>1m) and small (< 0.1m) components to an accuracy of < 100μm. The former involves metrological measurements for verification of the structural integrity of components such as aircraft wings during manufacture. The latter requires high density spatial mapping of precise machine components for reverse engineering or for inspection against a CAD model.

This paper describes an imaging system based on the time-of-flight principle, whereby the transit time of a short optical pulse scattered from a target is used to infer distance in the z-direction and appropriate imaging optics gives position in the x and y directions. The system uses the time-correlated single photon counting (TCSPC) technique with a passively Q-switched AlGaAs laser diode [1] as the optical source and a silicon single photon avalanche diode (SPAD) [2] as the detector. The TCSPC technique gives very high sensitivity, and its statistical nature allows a trade off between accuracy and measurement time. Typically, a 20μm repeatability for a single point is achievable in ~0.5 seconds, whilst 100μm requires ~0.01 seconds. Figure 1a) shows a photograph of the time-of-flight imaging system and fig. 1b) shows a high density surface scan.



(a) (b)

Fig. 1 (a) Time-of-flight system. (b) High density surface scan

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GALLIUM LANTHANUM SULPHIDE BASED GLASS FIBRES FOR PASSIVE MIR DELIVERY APPLICATIONS

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Applications such as remote sensing, imaging and laser power delivery (for medical or industrial applications) using mid infra-red wavelengths require stable and non toxic low loss MIR transmitting glass fibres. The silica transmission window extends to only 2μm making silica fibres unsuitable for such applications. Mid infra-red transmitting fibres are currently either fluorozirconate based, with the disadvantages of being hygroscopic, and a relatively small transmission window (~ 1-3μm), or As_2X_3 (X= S, Se) based with the disadvantage of toxicity should the fibre burn or degrade. Gallium lanthanum sulphide based glasses are proposed as high quality alternatives as they have a high glass transition temperature which results in increased stability, are non toxic, and have a wide transmission window of ~ 1-8μm [1].

One limiting factors in the performance of a fibre for the passive applications listed above is the optical loss of the fibre. This has three main physical causes: The electronic edge at the UV end of the spectrum is from electrons excited from the valence band across the bandgap of the material or to defect states in the bandgap, the fundamental glass absorption in the IR is from the multiphonon edge by excitation of optic phonon modes in the glass with phonon generation and subsequent photon absorption, and Rayleigh scattering caused by fluctuations in the refractive index of the glass caused by density and compositional fluctuations on a scale much smaller than the wavelength of light.

In this paper we present predictions for the minimum loss in glasses of composition; $70Ga_2S_3$:$30La_2S_3$, $72.5Ga_2S_3$:$27.5La_2O_3$ and $65Ga_2S_3$:25CsCl:$10La_2S_3$. Measurement of loss from the fundamental glass absorptions (The electronic and multiphonon edges) was achieved using a spectrophotometer and Fourier transform infra-red spectroscopy respectively with thin slices of the glasses. Rayleigh scattering properties were calculated according to the method of Lines[2] from material parameters. The minimum predicted loss is given by the addition of the loss due to Rayleigh scattering and fitted data of the fundamental glass absorptions. Fiberization of gallium lanthanum sulphide glasses is routinely possible and fibre loss measurements in the NIR and MIR are also presented.

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4. Spectroscopy and Sensing

SPECTROSCOPY OF A SINGLE YTTERBIUM ION

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A forbidden transition, in a single atom at rest in free space, is perhaps the ultimate spectral reference. Over recent years this ideal has been approached by laser cooling a single ion stored in an electrodynamic trap and observing a weak transition using quantum jumps.

In particular, the ytterbium ion is the most versatile of the various ion species under consideration, having clock transitions in the visible, infra-red and microwave regions of the spectrum. Further, the 171 isotope of Yb^+ has transitions free from the linear Zeeman effect which enhances the suitability as a reproducible standard.

The $^2S_{1/2}$ - $^2F_{7/2}$ electric octupole transition in Yb^+ is the narrowest feature in the optical spectrum. Recently this transition has been driven at the NPL [1]. Measurements show that the $^2F_{7/2}$ level has a radiative lifetime of 10 *years*. Therefore this transition has exceptional promise as a high stability frequency standard.

The $^2F_{7/2}$ - $^2D_{5/2}$ 3.43 μm transition has also been studied, with application to a mid-infra-red frequency standard [2]. The transition lies less than 1 THz from the 3.39 μm methane-stabilised He-Ne laser, making it a possible replacement for this standard. Narrow linewidth quantum jump profiles of this transition have been observed in this five laser experiment.

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TIME-RESOLVED SPECTROSCOPY OF PLASMAS GENERATED BY COPPER VAPOUR LASER ABLATION OF METALS

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The use of copper vapour lasers (CVLs), and other pulsed high average power lasers operating in the visible at high pulse repetition frequency (10 kHz upwards), for materials processing is becoming more widespread. Current understanding of direct coupling between intense optical fields (10^8 - 10^{10} W/cm^2) and solid target substrates is well understood in terms of material characteristics and can be described within a classical thermal model. However, the effect of the laser generated plasma (LGP) on the ablation process remains under investigation. In particular when processing with visible and UV laser sources, secondary effects in the plasma mediate the laser-material interactions, and ultimately set physical limitations to the accuracy and minimum dimensions attainable in laser micromachining applications.

Time-resolved atomic emission spectroscopy experiments on LGPs produced during laser-machining of common metals (aluminium, copper) were conducted to provide insight into the dynamics of ablation process. Due to the CVL delivering 2.5 mJ pulses at 10 kHz in the green-yellow (511 and 578 nm) spectral region, the signal-to-noise ratio needed to be enhanced considerably to compensate for the orders of magnitude difference in brightness. For this purpose a dual Czerny-Turner grating monochromator arrangement was used. By means of delay shutter control of the master oscillator - power amplifier CVL system, which is capable of delivering single or N-shot burst up to quasi-continuous operation at 10 kHz, the cumulative effect of subsequent pulses on the laser ablation process at high pulse repetition frequency was studied.

Results will be presented of recorded spectra from different atomic and ionic species exhibiting varying temporal characteristics. A comparison of the measured spectra with extensive numerical simulations[1] show reasonable agreement and provide information on the evolution of the electron temperature and electron density inside the plasma core. The signature of different spectral lines were found to be sensitive to changes in various process parameters, for example, positioning of the focal point and pressure of the ambient atmosphere. These effects may possibly be implemented for in-situ process control of laser-based micromachining applications.

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A SUB-1 kHz LINEWIDTH PROBE LASER FOR INTERROGATING THE $^2S_{1/2}$ - $^2D_{5/2}$ TRANSITION IN COLD TRAPPED STRONTIUM IONS

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Recent reductions in the observed linewidth of the $^2S_{1/2}$ - $^2D_{5/2}$ transition at 674 nm will be described. This transition has potential use as an optical frequency standard, although the natural linewidth of ≈0.4 Hz may only be realised with a sufficiently narrow 674 nm laser and control of other parameters such as magnetic field. This paper will discuss the latest results obtained with the laser interrogating the strontium transition.

The diode laser optical system has previously been described in some detail [1]. Two lasers are used, with one laser locked to an ultra-low-expansion (ULE) reference cavity and a tunable laser which is offset-locked to the first laser. Both lasers are pre-stabilised to confocal cavities using resonant optical feedback. The lock to the ULE cavity is a Pound-Drever arrangement with a modulation frequency of 2 MHz. Two similar lasers systems have been set up locked either to adjacent modes of the same ULE cavity, or to two different cavities. Preliminary results suggest that the laser linewidths are less than 100 Hz full width at half maximum when the two lasers are locked to the same cavity, but ≈1 kHz when locked to different cavities of nominally the same design. This may be due to vibration introduced in the mounting arrangement for one of the cavities. Laser tunability is obtained by offset-locking a second laser to a ULE-cavity stabilised laser. The offset-lock comprises a fast phase comparator operating close to a 15 MHz reference oscillator. This oscillator is programmable, allowing the laser frequency to be precisely controlled from a PC.

In order to obtain 674 nm transition linewidths of less than 1 kHz, careful consideration also needs to be given to the Zeeman structure of the Sr^+ transition. Whilst ambient DC magnetic fields can be compensated for using coils external to the trap, AC magnetic fields broaden the individual Zeeman components of this transition. A mu-metal shield has been constructed around the trap to reduce the ambient fields. Strontium transition features with linewidths of less than 1 kHz have been observed, limited mainly by the 674 nm laser linewidth.

ULE cavity frequency drifts over periods of over 1 year will be described. Low average drift rates of a few parts in 10^{11}/day are observed in two cavities. This is important to provide the short-term frequency stability of the probe laser for the ion-trap based optical frequency standard.

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THE APPLICATION OF A CONTINUOUSLY-TUNABLE, CW OPTICAL PARAMETRIC OSCILLATOR FOR HIGH RESOLUTION SPECTROSCOPY.

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In this paper we report, to our knowledge for the first time, the application of a smoothly-tunable, single-frequency, continuous-wave, optical parametric oscillator (OPO) for high-resolution spectroscopy.

The OPO is based on a KTP crystal, configured as a doubly resonant oscillator in a high Finesse cavity and has a pump threshold of only 30mW. The OPO is phased-matched to give type-II, near degenerate signal and idler outputs at 1μm. Angle tuning the KTP gives course tuning over approximately 100nm. Once the course tuning has been set to the spectral region of interest the cavity length is controlled, holding the OPO to a single signal and idler mode pair. The signal or idler output can be selected by a polariser and the output frequency can be tuned smoothly by tuning the pump laser. Using a tunable pump source relaxes the constraints on the OPO allowing continuous tuning within a single cavity. The advantage of using a doubly resonant oscillator is that the linewidth of the OPO matches that of the pump source. Hence the ultra narrow linewidth of the diode pumped source is transferred to the OPO.

The pump laser is an all-solid-state, frequency-doubled Nd:YLF laser with an output at 523nm of several 100's mW. The cavity design is such that simply by scanning the cavity length the output frequency can be tuned over 10GHz. This gives smooth and continuous tuning of the OPO over approximately 5GHz

To demonstrate the performance of our OPO we have recorded the absorption spectrum of cesium vapour in the 1μm spectral region. The 75mm long cell contains cesium with a purity of 99.95% , heated to 320°C. The transmitted OPO power is recorded as a function of frequency. Figure 1 shows the recorded cesium dimer (Cs_2) spectrum over a tuning range of ~4GHz. We are presently refining our experimental configuration to obtain Doppler-free spectral measurements.

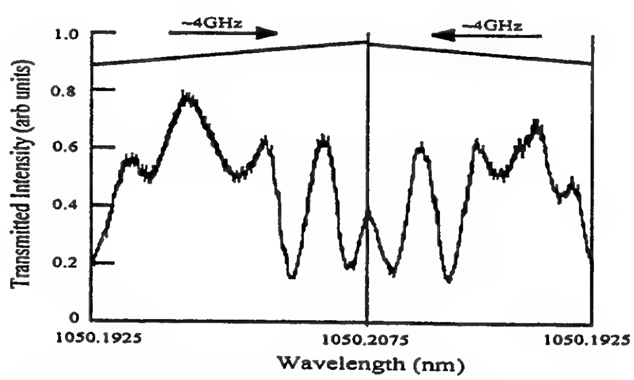

Figure 1. Absorption spectrum of cesium at 1050nm.

PROGRESS TOWARDS MID-INFRARED FIBRE LASERS IN RARE-EARTH DOPED GALLIUM LANTHANUM SULPHIDE GLASS FOR GAS SENSING AND REMOTE SENSING

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Diode-pumped rare-earth doped fibre lasers in the mid-infrared wavelengths region would offer a compact and efficient alternative to the either relatively weak or very complex existing mid-infrared sources such as thermal emitters, gas lasers and OPOs. A prerequisite for the rare-earth host material is a low phonon energy leading to mid-infrared transparency and to low nonradiative decay rates and therefore higher quantum efficiencies of mid-infrared transitions. Conventional silica glass fibres cannot fulfill these requirements leading to a need for new glass materials with lower phonon energies which must also be suitable for fibre pulling.

Our approach towards mid-infrared laser sources is based on the stable, non-toxic and non-hygroscopic chalcogenide glass gallium lanthanum sulphide (GLS) with the molar composition $70Ga_2S_3:30La_2S_3$ which has been pulled into fibre form successfully [1]. It has a low phonon energy (425 cm^{-1}) and a wide infrared transmission extending beyond 8 µm. The characterization of undoped GLS glasses and fibres such as loss measurements and theoretical loss calculations will be presented in another paper at this conference [2].

In this paper we present the spectroscopy of rare-earth doped GLS glasses and fibres which show fluorescence at wavelengths which are interesting for gas sensing and remote sensing. Examples are the 3.4µm emission from praseodymium and the 4.3µm emission from dysprosium which overlap with the strong fundamental absorption bands of methane and carbondioxide, respectively, and could therfore find application as gas sensors for these two important greenhouse gases. The emission of thulium at 3.8µm and holmium at 3.9µm fall into the atmospheric window with the highest transmission and could therefore be suitable for remote sensing applications.

Laser action an the above transitions has not been achieved to date but the first laser action in a rare-earth doped chalcogenide glass fibre which has been demonstrated in a neodymium doped GLS fibre shows the potential for mid-infrared fibre lasers in this chalcogenide glass system [3].

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PROGRESS ON THE DEVELOPMENT OF AN ULTRA-VIOLET STATIC FOURIER-TRANSFORM SPECTROMETER FOR THE DETECTION OF TOXIC GASES

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Air quality is a topic of growing concern to industry and the public alike. Within the petrochemical industry air quality takes on an additional importance because many of the gases potentially released into the atmosphere are not only highly toxic but explosive as well. Traditional technology uses many single point sensors but these are often confused by different gases and can fail without warning.

We have developed a Fourier-transform spectrometer with no moving parts which operates in the ultraviolet region of the spectrum. Wollaston prisms are used to form an interferogram in the spatial domain which is recorded using a detector array and subsequently Fourier-transformed to yield the optical power spectrum of the incident light. The spectrometer, light source and associated beam expansion telescopes have been incorporated into robust housings allowing them to be employed as an open path optical system for the detection of toxic gases.

This paper will present the latest results obtained with this instrument. Specifically we will report on the extension of this technology to cover other gases such as benzene and ammonia.

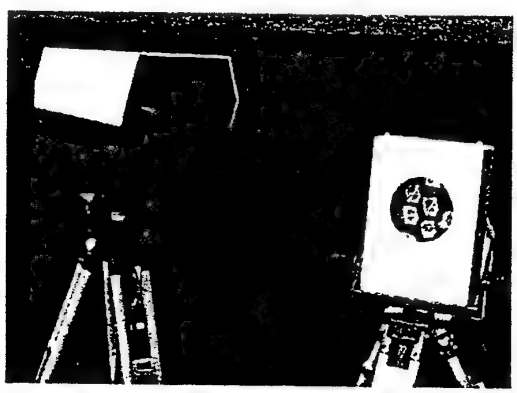

Figure 1. The open-path, ultra violet, Fourier-transform spectrometer and retro reflector

5. Coherent Processes

COHERENTLY INDUCED TRANSPARENCY AND INVERSIONLESS GAIN ON A BLUE PROBE IN A DOPPLER-BROADENED V-TYPE MEDIUM

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Experimental observation of cw coherently induced transparency on a blue probe field, controlled by an IR source is presented in a Doppler-broadened V-type system, based on atomic rubidium. Theoretical modelling confirms these observations and further predicts inversionless gain on the blue probe field.

It was recently shown, both theoretically and experimentally, that a cw coherently induced transparency feature could be observed in a Doppler-broadened cascade medium even when the probe and coupling fields had a wavelength mismatch of several hundred nanometers [1]. These observations are significant since they remove the matched wavelength requirement in cw atomic coherence experiments within inhomogeneously broadened media [2]. The explanation of this mismatched transparency rests on the interplay of quantum interference (E.I.T.) and Autler-Townes splitting.

Subsequent work includes a theoretical examination of the wavelength dependence of an induced transparency in a Doppler broadened V-type system. The most significant feature of this investigation is the fact that the transparency depth appears insensitive to the relative direction of the wavelength mismatch. Following the above result it is predicted that a 780 nm coupling field ($5S_{1/2}$ - $5P_{3/2}$) will induce a coherent transparency upon a 422 nm probe field ($5S_{1/2}$ - $6P_{3/2}$). Comprehensive experimental results verifying this prediction will be presented. A frequency doubled Ti:sapphire laser is employed as a probe beam with a second Ti:sapphire laser providing the coupling field. Transparency levels greater than eighty percent are achieved with a coupling field of 800mW. Significant optical pumping [2] is destroyed by collisional mixing of the hyperfine split ground state.

It is predicted that this coherently induced transparency feature could be enhanced, by moving population from the $5P_{3/2}$ level to the $6P_{3/2}$ level, so producing 422 nm inversionless gain. Movement of population is achieved by employing a 776 nm pump field, resonant with the $5P_{3/2}$ - $5D_{5/2}$ transition, so populating $6P_{3/2}$ via spontaneous decay. These results represent a significant step in moving from a matched wavelength inversionless laser [3] to the high frequency, mismatched, regime.

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Investigation of the role of EIT in four-wave mixing in Kr

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Summary

We have investigated a resonant four-waver mixing (fwm) scheme in krypton that generates vacuum ultra-violet (VUV) coherent radiation around 123.6nm. This involves two-photon resonantly enhanced sum-difference frequency mixing in Kr, with frequencies connected by the relation $\omega_4 = 2\omega_1 + \omega_2$. Our experiments were performed with $2\omega_1$ close to two-photon resonance and also ω_2 close to single photon resonance. The wavelength of the generated fields is therefore near to the 123.6nm resonance transition. The objectives of the work are to study the effects of dressing by the strong field at ω_2 on the frequency dependence of the non-linear response (i.e. appearance of Autler-Townes splitting of the resonance) and to examine the extent to which the accompanying electromagnetically induced transparency may play a role in enhancing the non-linear optical conversion efficiency. Photoionisation yield and VUV production efficiency were studied as functions of the frequencies and intensities of the two- and single-photon resonant fields employed.

An OPO pumped by a frequency doubled, injection seeded, Nd.YAG laser provides the field at ω_2 (at 758nm). This field is single-mode and near transform limited with a bandwidth <500MHz. Synchronized with this laser is an excimer pumped dye laser, the output of which is frequency doubled to provide the field at ω_1 (212.55nm). The two beams are made collinear and are weakly focused into a Kr jet (pressure 1-10mbar) from a pulsed gas valve. Coherent VUV radiation generated in the interaction is detected using a solar blind photomultiplier located at the exit slit of a monochromator. Simultaneously the ion current arising from photo-ionisation within the gas is monitored.

The dependence of the generated VUV intensity and photoionisation signal on the laser frequencies ω_1 and ω_2 and of the intensity of ω_2 were studied. These studies have revealed the effects of strong field dressing of the non-linear response of the medium and the accompanying EIT effect that reduces linear absorption and modifies the phase-matching in the medium. We have also observed a significant reduction in the photoionisation as the dressing laser field strength is increased. Latest results will be presented and discussed.

STIMULATED BRILLOUIN SCATTERING WITH AN INFRA-RED OPTICAL PARAMETRIC OSCILLATOR

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We present the results of experiments investigating Stimulated Brillouin Scattering (SBS) of the output of an infra-red Optical Parametric Oscillator (OPO).

SBS has been widely investigated as a means of phase conjugation of pulsed lasers with visible and near infra-red wavelengths. In particular application to Q-switched solid state Nd:YAG lasers operating at 1.064μm has been the subject of numerous studies.

It is of interest to see whether SBS phase conjugation can be used in conjunction with an infra-red OPO. OPOs are an important source of coherent radiation in the mid infra-red spectral region. However they tend to have broad gain bandwidths, limited only by phase matching considerations. Thus pulsed OPOs usually give broadband outputs which are not compatible with efficient generation of SBS. Building a line-narrowed OPO was therefore a prerequisite for these experiments. We used a KTP based OPO, pumped by an injection seeded Nd:YAG laser at 1.064μm, which resulted in a signal and idler at 1.9μm and 2.4μm respectively. A combination of a resonant reflector as an output coupler and active stabilisation of the OPO cavity length were used to line-narrow the output, resulting in single longitudinal mode operation with up to 1mJ of signal energy in a 20ns pulse. The signal energy was increased to 7mJ by a parametric amplifier stage using two KTP crystals with walk-off compensation.

SBS was observed at 1.9μm in the liquid $TiCl_4$, with a threshold energy of 3.5mJ and slope efficiency around 70%, although the limited energy at the signal wavelength meant that the maximum observed reflectivity was only 15%.

The SBS threshold of 3.5mJ at 1.9μm compares to a threshold of 1.2mJ at 1.064μm when the same SBS medium and focusing lens were used. There are two factors which increase the SBS threshold with increasing wavelength. Firstly diffraction effects become more important at longer wavelengths, which means that focusing in the SBS cell is less effective in increasing the intensity×interaction length product. Secondly the increasing phonon lifetime, which increases as the wavelength squared, means that the interaction becomes more transient as the wavelength gets longer. These factors result in a threshold energy that increases as the wavelength cubed for longer wavelengths. Thus for short pulse lasers the SBS threshold is predicated to rise rapidly for longer infra-red wavelengths.

DYNAMICS OF ORIENTATIONALLY ENHANCED POLYMERIC PHOTOREFRACTIVE COMPOSITES

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Material parameters for polymeric photorefractive materials have improved rapidly in the few years since the first report of the effect in a polymer based material in 1991[1]. Chemically stable polymer composite materials containing a high concentration of polar electro-optic dyes have been developed. These exhibit near unity diffraction efficiency[2] that is far in excess of values achieved for crystalline materials. The speed of response has been identified as important for many of the applications proposed for photorefractive materials including primary computer storage, optical correlation and optical amplification of modulated signals[3]. The speed of dynamic response of the polymeric materials studied to date are inferior to some crystalline materials such as $Fe:LiNbO_3$.

The photorefractive effect may be viewed as four processes: charge generation, charge transport, charge trapping and nonlinear response. In polymeric materials these functionalities are provided by different molecular species. This allows for tailoring of the photorefractive response through modification of composite constituents.

Characterisation of the associated time constant for each process and hence identification of the rate limiting step must, therefore, be considered the first step towards development of a class of materials with high speed dynamic response. The response dynamics of the individual processes for high diffraction efficiency composites are distinguished. The compound overall risetime dynamics associated with these materials are analysed in terms of these base processes.

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6. Optically Pumped Lasers

Ti:SAPPHIRE LASERS TRANSVERSELY PUMPED WITH A HIGH POWER COPPER VAPOUR LASER

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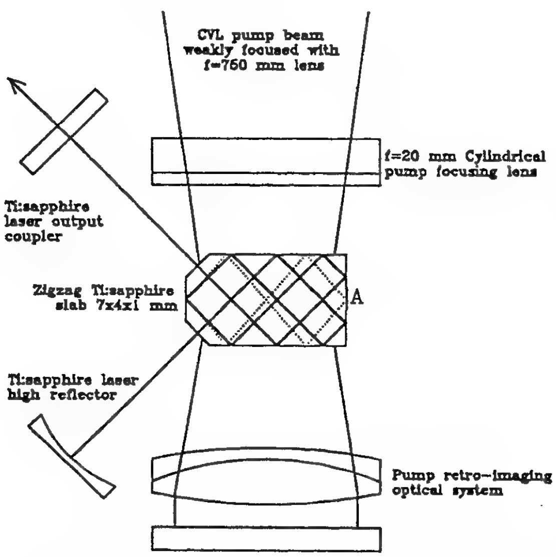
We present theoretical and practical investigations into the operation of Ti:sapphire lasers pumped by high average power (>50 W) poor beam quality (~500 times diffraction limit) CVLs. Hitherto CVL pumped Ti:sapphire lasers have been limited to pump powers of 20 W by damage to the crystal by the tightly focused pump beam. A new, transverse, pumping geometry has been demonstrated[1] to offer considerable advantages over the usual longitudinal geometry in terms of lack of crystal damage and tolerance of poor pump beam quality. The first, simple, transversely pumped Ti:sapphire laser designs[1] suffered from poor pump absorption in a crystal which was just 1 mm deep in the pumping direction. The zigzag slab laser design shown in the figure allows the use of a deep crystal, giving significantly better pump power absorption and providing large top and bottom crystal faces for cooling. With high power pumping it is very important to keep thermal gradients in the crystal to a minimum in order to minimise the adverse affects of thermal lensing on the Ti:sapphire laser beam. Computer modelling of the time evolving temperature profile in the crystal under pulsed pumping showed that thermal lensing could be completely eliminated by taking advantage of the excellent thermal properties of sapphire at 77 K. Interferometric measurements of the thermal profile in a Ti:sapphire slab at 300 K and 77 K have borne out the theoretical predictions. Lasing on the zigzag path (solid line) was observed with a pulse length of 10 ns and a power of 3.2 W at 6.2 kHz from 45 W pump. Output power was limited by an internal lasing mode, confined entirely within the crystal by total internal reflection (dotted line). This path has essentially no output coupling, and has a shorter build up time than the intended external cavity laser. Loss of inversion to this internal mode was observed by fluorescence imaging techniques. It is believed that this is the reason for the lower than expected output power. Current investigations are being undertaken to frustrate the internal mode by preventing the reflection at point 'A', which is used only by the internal mode, in order to achieve higher output powers.



1. W.J.Wadsworth, D.W.Coutts and C.E.Webb, **Novel Geometries for Copper Vapour Laser Pumped Ti:sapphire Lasers**, TOPS Volume 1 *Advanced Solid State Lasers*, OSA 1996

A 2 W 6.2 kHz FIBRE-END-PUMPED TITANIUM SAPPHIRE LASER

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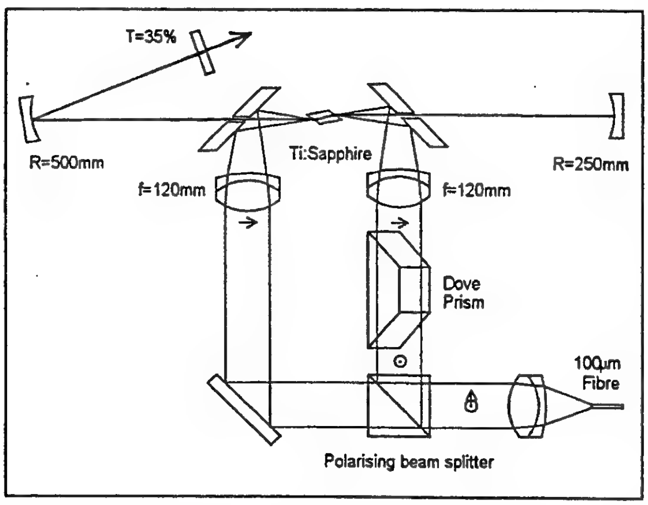
Efficient gain-switched operation of titanium sapphire lasers pumped with few-millijoule pulses requires very tight control over the pump volume (typically 10 mm long by 50-300 μm diameter). Well-defined, stable mode-matching is usually achieved with a very high beam quality green pump laser. We have developed a fibre-end-pumped Ti:sapphire laser whereby the pump laser beam quality requirements are reduced to the easier task of coupling the pump laser beam into an optical fibre.

An arrangement similar to that developed by Takehisa and Miki[1] for Ti:sapphire laser pumping with a copper vapour laser having very low beam quality has been adapted for fibre pumping. In this system (figure 1), the focused pump beam is coupled into a Brewster cut Ti:sapphire laser crystal by reflection of a 45° mirror with a small central hole positioned such that the Ti:sapphire laser cavity mode may pass through unobstructed. For fibre pumping, the output from a 100μm core diameter fibre was recollimated and then split into two orthogonally polarised beams using a polarising beam splitting cube. A dove prism was used to rotate the polarisation of one beam such that both were horizontally polarised. Using two centre-hole pump coupling mirrors and a pair of ~100 mm lenses double-end pumping was achieved. A simple 0.6 m long astigmatically compensated three-mirror cavity with a 65% reflectivity output coupler was used on the Ti:sapphire laser.

Using a 6.2 kHz copper vapour laser master oscillator - power amplifier system, typically 13.6W (2.0 mJ) pump power was delivered by the optical fibre corresponding to 75% coupling efficiency. Note that in recent experiments, Oxford Lasers has developed a system delivering 10 W average power from a 100 μm fibre using a single copper vapour laser device[2].



Average Ti:sapphire laser output powers up to 2 W were obtained at 15% absolute efficiency from the fibre-delivered pump power. Pulse durations were typically 30 ns with pulse stability of ~5%. The fibre pumping arrangement has proved to be a very robust geometry where the pump laser is now mechanically decoupled from the Ti:sapphire laser. Details of the Ti:sapphire laser performance will be presented.

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THERMAL LENSING IN HIGH-POWER END-PUMPED Nd:YLF LASERS

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One of the major limitations of scaling diode-end-pumped solid-state lasers to high powers is introduced by thermal effects. An attractive feature of Nd:YLF has been its superior thermo-optical properties compared to other laser crystals. This is due to a decrease of refractive index with increasing temperature, creating a negative thermal lens, which partially compensates for the positive lens due to bulging of the rod end faces. Other advantages of Nd:YLF include its natural birefringence and its long fluorescence lifetime. The latter feature is of interest for high-power Q-switched operation. Problems in realising the true potential of the laser, however, have often been encountered, for underlying spectroscopic reasons as indicated, e.g., in [1].

We investigated the thermal lensing under lasing and non-lasing conditions within a diode-bar-pumped system. Under non-lasing conditions the thermal lens was measured using a Nd:YAG probe laser which double-passed the Nd:YLF rod. The resulting change in beam divergence was measured. Under lasing conditions the laser-beam waist size on the output coupler was measured. Hence, using the ABCD-matrix formalism, focal-length values for the thermal lenses were determined. The results showed a significant difference in the thermal lens under lasing and non-lasing conditions. In the former case a weak thermal lens was observed which varied linearly with pump power. Under non-lasing conditions a much stronger thermal lens was measured, whose power increased non-linearly with pump power. With 11 W of pump power incident on the crystal, a factor of 6 difference between lasing and non-lasing values of focal length was determined (π-polarisation, plane perpendicular to c-axis).

These measurements demonstrate that significant additional heat is generated in the non-lasing case. A finite-element calculation, which considered the relevant processes including interionic upconversion, their contribution to thermal loading, as well as the temperature distribution in the Nd:YLF crystal, was performed. An experimentally observed fluorescence saturation at 1.05 µm of more than 50 % under Ti:sapphire pumping was numerically reproduced, and the value of the published upconversion parameter [2] was thereby confirmed. With this information, the heat generation, spatial temperature distribution, and thermal lens under diode pumping were determined. The calculated thermal lens powers were in reasonable agreement with experimental results. Upconversion processes as well as the temperature dependencies of heat conductivity and thermo-optical parameters were found responsible for strong thermal lensing under non-lasing conditions and its non-linear behaviour with respect to absorbed pump power. Design improvement by a significant decrease of thermal lens power and spherical aberrations under Q-switched conditions can be achieved by increasing the pump-spot size, decreasing the dopant concentration and using a longer crystal, or detuning the pump wavelength from the absorption peak.

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THEORY AND DEVELOPMENT OF A DIODE LASER PUMPED 2.8-µm CW Er:YLF LASER

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Due to the strong absorption of light at a wavelength of approximately 3-µm in water there has been considerable interest in the development of new lasers that emit at that wavelength for use in medical applications, including surgery. Erbium doped into various garnet and fluoride crystal hosts will emit at wavelengths in the range 2.7-µm to 3-µm despite unfavourable lower laser level lifetimes in these materials.[1,2] Several two-ion energy transfer processes act to recycle ions in the lower laser level back into the upper laser level. In addition a Boltzmann distribution determines the population densities of the Stark levels in the upper and lower laser levels. These effects enable a population inversion between Stark levels in the upper and lower laser levels.[3]

A computer model has been developed consisting of rate equations for seven energy levels of Er^{3+} ions.[4] The model was used to investigate the Er^{3+} concentration dependence of the important energy transfer processes and hence the concentration dependence of the performance of cw operated Er:$Y_3Al_5O_{12}$ (YAG), Er:$Y_2Sc_2Ga_3O_{12}$ (YSGG), Er:$LiYF_4$ (YLF) and Er:BaY_2F_8 (BaYF). Threshold and slope efficiency calculations were also carried out for cw and pulsed operation of these materials for pump wavelengths of 795 nm and 975 nm. The poor performance of cw operated Er:YLF and Er:BaYF doped to high Er^{3+} concentrations cannot be explained by two-ion energy transfer processes alone.[2] The potential influence of three- and four-ion energy transfer processes on the cw performance of Er:YLF was investigated. It was determined that a four-ion process was most likely to explain low efficiencies at high Er^{3+} concentrations.

A diode pumped Er:YLF laser was constructed to test the computer model. Three Er:YLF crystals of different lengths were end-pumped at a wavelength of approximately 970 nm with the emission from a cw 1-cm diode bar focused down to a spot size of approximately 600-µm. Results of laser performance under varying experimental conditions will be reported and discussed in relation to the theoretical model.

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EFFICIENT CW AND Q-SWITCHED OPERATION OF A 946nm Nd:YAG LASER PUMPED BY AN INJECTION-LOCKED BROAD AREA SEMICONDUCTOR LASER

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Much interest exists in lasers based on the 946-nm $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in Nd^{3+}, despite the problems of reabsorption losses and low stimulated emission cross section, as their output can be frequency doubled to give blue light at 473nm. Although highly attractive as pump sources for such lasers, broad area diode lasers suffer from poor beam quality, limiting the effective exploitation of the high efficiencies potentially available from end pumped operation. In the case of 946nm Nd:YAG lasers this further compounds the limitations on efficiency due to the material properties.

Injection-locking with a single-mode diode master laser is a widely used technique for improving the spatial and spectral output of broad area diode lasers and laser diode arrays [1]. We have used a single-mode diode laser (SDL-5412) to injection-lock a 100µm wide broad area diode laser (SDL-2362) and obtain over 400mW output in a beam having an M^2 value of around 1.2 in the plane of the junction. The spectral width of the output was reduced from over 2 nm to less than 30 MHz.

Using the output of this injection-locked system to end pump a 946nm Nd:YAG laser, up to 120 mW of cw output has been obtained with a threshold of 31mW and slope efficiencies of 37% in terms of incident power and 54% in terms of absorbed power [2]. These results represent a significant improvement over similar systems pumped with free-running laser diode arrays, which typically have efficiencies in the region of 15-25% in terms of incident pump power, and approach efficiencies obtained when pumping with infra-red dye lasers [3,4]. The laser has also been actively Q-switched with 365mW of cw pump power giving 30ns, 175W peak power pulses at a repetition rate of 1.5 kHz. The Q-switched output has been externally doubled in critically phase matched $KNbO_3$ at room temperature to give an average output of 1.5mW at 473nm corresponding to 50W peak power pulses.

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EFFICIENT 1123nm DIODE-BAR PUMPED Nd:YAG LASER

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Laser emission at 1123nm has a number of possible applications, the most notable being differential absorption water vapour LIDAR, to remotely sense concentrations of water vapour in the atmosphere. For this application use is made of two different wavelengths, one, at 1123.06nm which coincides with a weak absorption peak of water vapour, while the other at 1123.2nm which falls in a region of very low water absorption. Nd:YAG provides the possibility for laser emission at both of the required wavelengths, and has been recognised as a suitable laser source for such a system[1]. However the emission cross-section of Nd:YAG at 1123nm is very small, approximately one fifteenth that of the 1064nm line, hence resulting in very low gain. Thus to achieve efficient laser operation at 1123nm, a very bright pump source is required so that intense pumping can be achieved. In this paper we describe a diode-pumped Nd:YAG laser pumped by such a bright source. The pump-diode used was a 7W diode-bar operating at 807nm. manufactured by the Opto-Power Corporation. The diode emission, which came from a 4.6mm wide region, was reshaped using the previously reported two-mirror 'beam-shaping' technique[2]. The resulting beam had 5.6W of power. was approximately circular. and had M^2 values of ≈20 and ≈40 in orthogonal directions. This was used to end-pump a 10mm long Nd:YAG rod, housed in a water-cooled heat-sink. To obtain intense pumping, the pump light was focused to a spot size of radius 130μm. The small spot-size results in a strong thermal lens in the laser rod, measured to have a focal length of ~55mm, but also being significantly aberrated, and thus requiring care over the choice of appropriate resonator. This Nd:YAG laser producing an output of 1.6W at 1123nm, in a linearly polarised, diffraction limited gaussian beam, from a standing wave cavity. This is around a five-fold increase in power on previous reports for this wavelength[3]. Narrow linewidth emission is required for a working LIDAR, thus a unidirectional ring cavity was constructed to enable single frequency operation. This produced 180mW of single frequency diffraction-limited output, which could be tuned to the wavelengths of interest. Due to a lack of suitable components (e.g. a low loss Faraday rotator), this performance is far from optimal. Further improvements will be discussed.

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7. X Ray and TW Lasers

AN ADVANCED PULSE GENERATOR AND PREAMPLIFIER FOR THE HELEN LASER

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A replacement for the HELEN laser has been proposed that would involve a considerable enhancement of performance up to 100TW from 32 beams. The design for the new laser is to be based on the technology being developed for the US National Ignition Facility (NIF). The pulse generation and preamplification stages employ novel technologies and represent a significant departure from previous designs. As part of the laser replacement development programme a pulse generator and preamplifier have been built and installed on the HELEN laser at AWE. As well as providing experience of the technologies involved, this system represents a significant enhancement of the performance of HELEN.

The system installed is based on the pulse generator and preamplifier developed at LLNL for the Beamlet laser as a laser physics demonstration of the technology for NIF. The initial laser pulse is generated by a laser diode-pumped Q-switched Nd:YLF ring oscillator. The output from this oscillator is fed by polarization maintaining optical fibre to an integrated optics waveguide modulator. Within this device, a product of the telecommunications industry, two amplitude modulators are used to temporally shape laser pulses of duration from 200ps up to 10ns. The electrical modulating signals are low voltage (less than 10V). A variable impedance transmission line is used to produce a variety of monotonically rising pulse shapes. More recently, a requirement for approximately Gaussian pulses of 1ns duration has been achieved by driving one of the amplitude modulators with a voltage equivalent to a phase retardation of 2π instead of π, thus returning transmission to a minimum by the end of the laser pulse. A modified transmission line was developed to provide the required voltage. The pulses exiting from the integrated modulators are necessarily of low peak power in order to avoid damage to the modulators themselves. A high gain ring regenerative amplifier is therefore used to raise the pulse energy to a level suitable for injection into the HELEN laser. The ring oscillator, integrated modulators and regenerative preamplifier have together achieved outputs of up to 12mJ in a 3ns pulse with stability of less than 5% rms. A range of different pulse shapes have been demonstrated. These performance characteristics will allow HELEN to be driven to its full capability for a range pulse lengths in excess of 1ns. This capability, along with the ability to provide pulses of varying temporal shape, represents a significant increase in the performance of the HELEN laser. Details will be presented showing the performance of the pulse generator and preamplifier itself and of the consequent enhanced performance of the HELEN laser.

Abstract for the 13th National Quantum Electronics Conference, 8-11 September 1997, Cardiff

NEW DEVELOPMENTS IN NI-LIKE X-RAY LASERS AT RAL

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Saturated x-ray lasers at shorter wavelengths are required for holography, microscopy, interferometry, radiography and many other applications. Although saturation have been observed in Ne-like x-ray lasers at 15 - 20 nm, they are difficult to scale to the shorter wavelengths with the currently available laser driver energy. Ni-like x-ray lasers, in principle, provide much shorter wavelengths for the same amount of driver energy because of the higher quantum efficiency, but saturated operation has not been demonstrated.

We report here the first demonstration of saturation in Ni-like Ag, In, Sn and Sm x-ray lasers at 14.0, 12.6, 12.0 and 7.3 nm respectively. The x-ray lasers from a refraction compensating double target were driven at 20 $TW \cdot cm^{-2}$ by a pair of 75 ps Nd-glass laser pulses separated by 2.2 ns. Using high-resolution spatial imaging and angularly resolved streaking techniques, the output source size as well as the time history, divergence, energy and spatial profile of the output beam have been fully characterised. The narrow divergence (~1 mrad), short pulse duration (~40 ps), high efficiency ($\sim10^{-6}$) and high brightness ($\sim10^{25}$ $photons \cdot s^{-1} \cdot mm^{-2} \cdot mrad^{-2}$) of these Ni-like x-ray lasers make them ideal candidates for many x-ray laser applications.

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MEASUREMENT OF DIRECT DRIVE LASER IMPRINT IN THIN FOILS BY XUV RADIOGRAPHY USING AN X-RAY LASER BACKLIGHTER

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A critical factor influencing the feasibility of ignition of direct drive inertially confined thermonuclear fusion is the seeding of Rayleigh Taylor (RT) growth of surface perturbations by imprint from laser intensity variations [1]. We have applied a new technique to study the imprint of a direct drive laser beam on a thin foil using an x-ray laser as an XUV backlighter [2]. We used multilayer XUV optics to image the foil modulations onto a CCD camera. This technique allows us to measure small fractional variations in the foil thickness. We determined the imprinted modulation and growth due to a low intensity ($I = 5\cdot10^{12}$ W/cm^2) 0.53 μm drive beam incident on a 2 μm Al foil using a germanium x-ray laser [3] at the Vulcan facility. Smoothing techniques such as RPP, SSD and ISI were used to minimise the optical perturbations and the growth rates for the different smoothing schemes are compared.
Moreover, single mode perturbations with λ = 15, 30, 70 and 90 μm wavelengths have been investigated to gain better insight into the physical processes of imprinting. It can be shown that growth rates for the 15 and 30 μm single modes are described by the well established Takabe formula [4], while the long wavelength modes do not exhibit any growth at all, which is due to the thin target.

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FREQUENCY DOUBLING OF PICOSECOND PULSES ON THE VULCAN LARGE APERTURE CHIRPED PULSE AMPLIFICATION LASER SYSTEM

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A feasability study of frequency doubling the VULCAN short pulse ~ ps, chirped pulse amplified (CPA) 1.054 nm beam for laser matter interaction studies was carried out at RAL. Interest in using the second harmonic of the CPA Nd:glass laser system arises for a number of reasons. There is a reduction of the pedestal level by virtue of the non-linear nature of the doubling process and a shorter wavelength interaction beam can be advantageous in laser-plasma experiments. For the fundamental CPA beam used during this experiment a focused target irradiation of 10^{19}W/cm^2 has already been demonstrated [1].

KDP crystals of various thickness between 1-4mm were characterised at incident intensities up to 3 x 10^{11} W/cm^2. The crytals used type I phase matching which has almost equal group velocities for the fundamental and second harmonic components. Type I frequency conversion facilitates experiments where contrast ratios > 10^6 are required for laser matter interactions, since it is easier to separate the orthogonally polarised fundamental and second harmonic components. Results on the second harmonic energy, conversion efficiency and beam focusability will be presented for the various test crystals as a function of power density and pulse length of the drive laser.

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IOP National Quantum Electronics Conference (QE 13)
University of Wales, Cardiff, September 8-11, 1997

VULCAN: A UNIQUE SYSTEM DELIVERING 250 TW AND FOCUSED TO GIVE INTENSITIES OF 10^{20} Wcm^{-2}

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The VULCAN high power laser system is a multi-beam Nd:glass system delivering pulselengths as short as 1 ps and capable of multi-terawatt operation. Short pulse (ps) generation at high intensities is achieved using the technique of chirped pulse amplification (CPA)[1] which avoids the problems associated with ultrashort pulse propagation in a non-linear amplifying medium by stretching the pulses prior to amplification.

We describe an upgrade to the system designed to increase the output to 250 TW in a 400 fs pulse. The system uses a commercial Ti:Sapphire oscillator which is pre-amplified in either a Ti:Sapphire regenerative amplifier or in multi-passed Nd:glass rods. The pulse is injected into the front end of the VULCAN laser and amplified to >100 J in a beam of 130 mm diameter. The pulse is compressed using large aperture diffraction gratings (420x210 mm) and then focused on to target using an off-axis parabola giving a focal spot size of ~15 microns.

An interaction chamber will be described which has been designed specifically for a broad range of experiments to be performed. These include: fundamental gas and solid target interactions; x-ray lasers; short pulse ignitor physics; high harmonic generation; and laser based particle acceleration techniques.

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The VULCAN Laser System 250 TW Upgrade
- Ultra High Power Pulse Diagnostics -

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ABSTRACT

VULCAN is a multi-beam ultra high power Nd:glass laser system that is capable of amplifying sub pico-second pulses to high energies using CPA. Typical single beam pulse powers are 35 TW which, when focused, produce power densities in excess of 10^{19} Wcm^{-2}.

VULCAN is currently undergoing an upgrade to increase the single beam output power to 250 TW. The upgrade is close to completion and this will result in power densities of 10^{20} Wcm^{-2}.

An important aspect of the upgrade is the single shot diagnosis of the ultra high power pulse. We report in this communication on the development of state of the art diagnostics to fully characterise the pulse at various stages of the laser system, from the front end right through to target delivery.

Key elements that have been addressed are pulse length, pulse energy, CPA recompressability, pulse contrast, spectral modification, multi beam timing and synchronicity, beam pointing, target plane beam quality, wavefront structure, pre-pulse monitoring and near field quality.

8. High-Power and Parametric Effects

BEAM CHARACTERISTICS OF AN ANNULAR CO_2 LASER

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Annular geometries for waveguide CO_2 lasers with radio frequency excitation and diffusion cooling form an attractive, ultra compact alternative to their rectangular counterparts. Using a novel method of RF excitation, we have demonstrated an annular laser which allows length scaleability of annular discharge with a narrow gap (~2 mm). The optical waveguide resonator is formed by two plane end mirrors, a polished aluminium inner electrode and an alumina ceramic outer electrode. This laser is expected to produce azimuthally polarised coaxial waveguide modes. These are closely related to a Bessel Beam. The diffraction properties of the zeroth azimuthal order Bessel beam are known to compare well with the fundamental Gaussian beam.

In this work we present the propagation properties of ideal coaxial waveguide laser modes, calculated in cylindrical co-ordinates using the Fresnel approximation to the Huygens' integral. Fig. 1 is example of the near and far field laser profile of such a mode. When the mirrors are well-aligned in the actual laser, the output is found to be a set of incoherent sections which are radially guided but free-space in the azimuthal direction. However, higher order azimuthal waveguide modes are produced when the laser cavity mirrors are tilted. These effects are thought to be due to non-concentricity of the waveguide, non-azimuthally uniform discharges and other constructional errors.

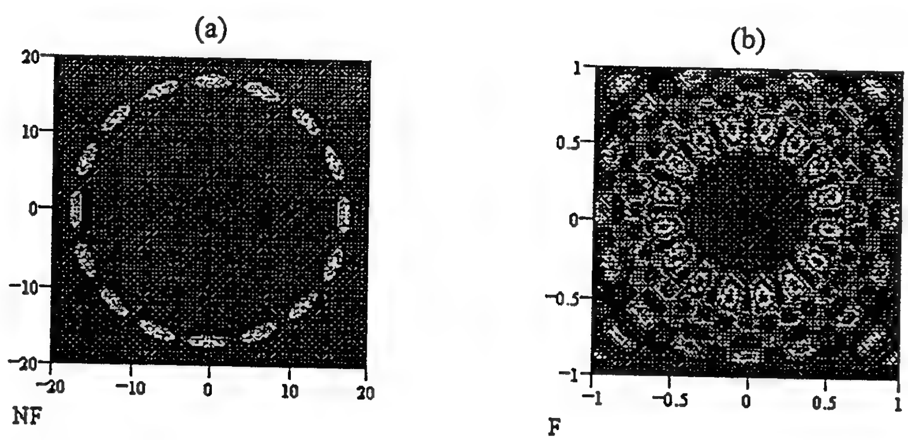

Figure 1. (a) Near field profile for azimuthal order 8 (b) resulting far-field pattern.

GENERATION AND PROPAGATION OF HARMONICS USING BESSEL-GAUSS BEAMS

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We have calculated, for some special cases of interest, far-field profiles, temporal profiles and conversion efficiencies for harmonics generated in a gaseous medium, extending an integral method introduced in Ref. [1] to the time-dependent propagation equations. As fundamental beam we have considered a Bessel-Gauss beam [2] which combines the features of both a Bessel beam [3] and a Gaussian beam. In the loose focussing limit, Bessel-Gauss beams can be regarded as a realistic realization of diffractionless beams, which in practice have a finite-sized diffractionfree zone [4,5]. In addition, the paraxial approximation has been relaxed, where appropriate, to adapt the Bessel-Gauss beam and to describe the far-field profiles off-axis more accurately.

We have considered in particular third-order harmonic generation in atomic hydrogen, for a fundamental wavelength of $\lambda = 355$ nm. The fundamental field couples the 1s and 2p states at about 1.15×10^{13} W/cm^2 through a 3-photon Stark-shift induced resonance [6]. We have taken into account dressed atomic susceptibilities (including absorption), non-perturbative dipole moments and ionization in the Sturmian-Floquet approach [7]. Besides comparing Bessel-Gauss and Gaussian beams with respect to phase-matching, we have investigated the importance of the dressed atomic susceptibilities compared to the (usually dominating) electronic contributions. To this aim, the conversion efficiencies have been calculated, both including and excluding atomic and electronic susceptibilities. The depletion due to ionization has also been taken into account. Together with an outline of the basic theory we present the results of these calculations and discuss them both for the Bessel-Gauss and the Gaussian beam, showing that in our particular case, the Bessel-Gauss beam performs better than a Gaussian beam at equal total power. Comparison with previous work about third harmonic generation using Bessel beams [8,9] is also made.

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HIGH POWER, CONTINUOUS-WAVE, SINGLY-RESONANT, INTRACAVITY OPTICAL PARAMETRIC OSCILLATOR.

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Continuous-wave singly-resonant intra-cavity optical parametric oscillators (ICSROs) present a novel solution to the generation of tunable, amplitude and frequency stable, coherent cw radiation in the infrared at watt-level output powers [1],[2]. High threshold pump powers may be overcome by utilising the large circulating fields available within the pump laser resonator, placing cw SROs within the power capability of widely established laser sources. This paper outlines the development of a high power tunable infrared source based on a Ti:sapphire pumped, KTA-based cw ICSRO exhibiting 90% down-conversion of the optimum laser output and generating as much as 1.4W of tunable near to mid-IR radiation.

The ICSRO is located within the cavity of an argon-ion pumped standing-wave Ti:sapphire laser. High circulating fields are achieved by specifying that all cavity mirrors are highly reflecting at pump wavelengths (0.75 - 0.9 μm). A tightly focused beam waist is located within an 11.5 mm KTA crystal and the SRO cavity is discriminated by a dichroic beam-splitter (BS) which is HR for the resonant single frequency signal field and HT for the pump field.

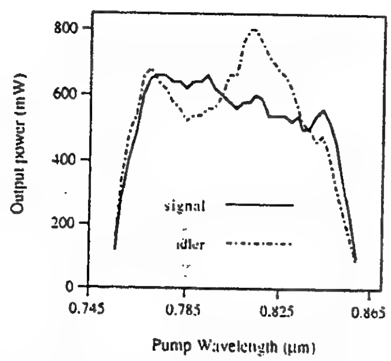

Figure (1) KTA SRO output power spectrum

With all SRO mirrors specified HR at signal wavelengths the device operates with a circulating pump threshold of ~ 14W corresponding to an argon-ion input power of 3.1W. Non-critical phase-matched tuning ranges, limited by coating bandwidths, of 1.1 - 1.25 μm (signal) and 2.3 - 3.0 μm (idler) have been demonstrated by pump tuning from 745 - 882 nm; and a total down-converted power of ~ 3.5W at 14W of argon-ion pump power (90% of the optimum Ti:sapphire output at that power) has been achieved. Useful extraction of the single frequency resonant signal field has been demonstrated by use of a ~ 1.1% output coupler. Extracted power levels (figure (1)) are in excess of 500 mW for both signal and idler over the range 1.114 - 1.192 μm (signal) 2.442 -2.821 μm (idler) for an argon-ion pump power of 14W. Through an optimum choice of crystal length and focusing parameters, the ICSRO approach for near to mid-IR generation is well within reach of all solid-state pump technology.

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FEMTOSECOND OPTICAL PARAMETRIC OSCILLATOR BASED ON PERIODICALLY POLED LITHIUM NIOBATE

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Frequency conversion using periodically poled lithium niobate (PPLN) has been widely reported recently, but to date, pulsed optical parametric oscillation has been confined to the nanosecond [1] and picosecond [2] regimes. We have achieved femtosecond pulses from a PPLN OPO, synchronously pumped by a self-modelocked Ti:sapphire laser. The OPO is configured as a v-cavity, using a crystal 11 mm by 0.5 mm by 1 mm in length, with eight gratings having periods ranging from 20.5 μm to 22 μm.

Periodic poling and quasi-phasematching allow a wide range of phase-matchable wavelengths from a single crystal; we have been able to fully exploit this by using a total of five mirror sets in the OPO. In this way we have generated an almost continuously tunable output from 975 nm to 4.55 μm. The tuning was achieved solely by varying the cavity length; a change in length of about 3 μm was sufficient to tune over the bandwidth of each mirror set. Oscillation was readily achieved at room temperature, but significant photorefractive damage was observed. This was eliminated by heating the crystal to 100°C, which greatly improved the stability of the OPO. A threshold of 45 mW was measured. Conversion efficiencies are moderate, with 90 mW of signal power and 53 mW of idler power generated from 1.35 W of incident pump power. Additionally, operation at the higher temperature produced sufficient thermal expansion of the PPLN to change the grating periods to those needed for phasematching of second harmonic generation of some signal wavelengths. 60 mW of green light at 540 nm have been measured as a result of this.

Autocorrelation measurements of the signal pulses indicated pulse durations of the order of 350 fs. The pulses are highly chirped, corresponding to self-phase-modulation observed in spectral measurements. The degree of chirp varies significantly with wavelength, according to changes in signal power and dispersion. The addition of dispersion compensation to the cavity, in the form of a prism pair, removed the chirp and produced near-transform-limited pulses of 140 fs duration.

In summary, we have demonstrated a low-threshold, very widely tunable femtosecond source based on optical parametric oscillation in PPLN.

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ALTERNATIVE MEDIA AND COMPETING PROCESSES IN ULTRA-BROADBAND LIGHT GENERATION

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Non-parametric stimulated Raman scattering is well-established as a simple and efficient method of converting laser radiation to one or more lower (Stokes) frequencies. However, parametric Raman conversion to higher frequencies, or the simultaneous generation of multiple Raman lines, has generally been found to be much less efficient. We have shown that the collinear generation of higher orders, using two pump beams (of frequency difference resonant with the Raman transition) which are temporally symmetric (of matching intensity and shape), has much greater potential. Considering hydrogen gas, the generation of a single multifrequency beam consisting of around 50 waves of comparable energy is feasible [1]. More recently, we have extended our analytic work, dealing with steady-state multifrequency generation, to include transient effects [2]. We shall present simulation data which demonstrates the validity of this new analytic result and the role played by additional processes, such as dispersion.

The possibility of using air as the Raman medium has obvious attractions. Experiments, using only one pump beam, have shown that multifrequency light containing around 15 distinct waves can be generated [3]. However, our analyses predict that (resonant and symmetric) two beam pumping of atmospheric nitrogen has the potential to generate light containing around 250 distinct frequencies [4]. Furthermore, we find that the necessary input intensities are one or two orders of magnitude lower than those used in [3]. We shall present a brief summary of these results and, also, their extension to the consideration of cooled nitrogen. In this latter case, we find that there is a potential for generating bandwidths of around 500 distinct waves.

Finally, we shall present further new results which address the key question of the role of unwanted competing nonlinear processes. For single pump beam configurations it is well known that spontaneous, or seeded, scattering from other (rotational and vibrational) molecular transitions may become significant. Specifically, we have examined the role of competing processes arising from spontaneous scattering, from large amplitude seeds (amplified spontaneous emission or scattering from optics) and, also, the parametric generation of unwanted sidebands. Furthermore, we have assessed self- and cross-phase modulation effects. A full account of these results will be presented.

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EFFICIENT OPERATION OF A SYNCHRONOUSLY-PUMPED OPTICAL PARAMETRIC OSCILLATOR IN PERIODICALLY-POLED LITHIUM NIOBATE OVER THE RANGE 1.33µm - 4.8µm

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Periodically-poled lithium niobate (PPLN) is proving to be a very versatile and effective nonlinear optical material. It has a high nonlinearity (~20pm/V) and offers non-critical phase-matching over its entire transmission range. In the first experiments demonstrating synchronously-pumped parametric oscillation[1] in PPLN, the tuning range achieved using a 1047nm pump (from a mode-locked Nd:YLF laser) covered 1.67µm - 2.806µm (signal+idler), using 6mm long PPLN samples that we had fabricated by electric field poling. In the experiment reported here, we have used longer samples (19mm, fabricated by Crystal Technology). This has resulted in lower thresholds, now down to as low as ~8mW of mean pump power at 1047nm. We have also used shorter grating periods, thus allowing a considerable extension of tuning range, now covering 1.33µm - 4.81µm.

The efficient performance of the OPO at the long wavelength limit is particularly notable. PPLN allows extension to longer wavelengths than bulk lithium niobate since the IR absorption edge for the extraordinary polarisation (as used in PPLN) is at a longer wavelength than for the ordinary polarisation[2]. While the infrared absorption of $0.75cm^{-1}$ at 4.8µm is already significant for our 19mm PPLN sample, the long-wave limit for oscillation was, in fact, set by the shortest grating period available and not by the IR absorption.

It is the high-gain available from PPLN, helped by the long sample and mode-locked pump, that allows operation well into the region of IR absorption. Thus, pumping with a mode-locked 1047nm Nd:YLF laser (4ps pulses, 120MHz, ~1W mean power, Microlase DPM-1000-120), a threshold (mean incident power) of only 80mW was achieved for 4.8µm generation. An available output of 40mW was measured at 4.8µm for 800mW of incident pump power.

The observed pump depletion was ~75%, a level which was maintained or exceeded across the entire tuning range, implying that over 100mW of 4.8µm power was generated, of which some 60% was lost by IR absorption and reflection at the PPLN AR coating.

Based on these performance figures we calculate that, allowing for the increased IR absorption, this PPLN device could be usefully extended even beyond 5µm, thus covering an extensive and important range in infrared spectrum.

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HIGH HARMONIC GENERATION AND PERIODIC LEVEL CROSSINGS

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The generation of high harmonics in the spectra of strongly laser-driven atoms has inspired much experimental and theoretical development in the past few years [1]. The generation of a broad plateau of harmonics appears to be most effective if the laser intensity is such that tunneling of electronic wave packets from the laser-deformed atomic potential is repeated many times in a phase-locked fashion. This observation provides the foundation for the very successful "recollision picture". Nevertheless, there are simple models of high harmonic generation which also predict a plateau and a cut-off, but have no apparent connection with the recollision model. One of these simple models is that of a two-state atomic system driven by a strong laser field whose frequency is much less than the atomic transition frequency, where the generic plateau and cut-off is once again reproduced [2].

The purpose of this paper is to introduce a periodic level crossing model of the strongly-driven two-level atom which explicitly contains repeated encounters, phase-locked to the laser driving field which are remarkably reminiscent of the recollision model. Using this model we establish the relationships between multiple Landau-Zener crossings of energy levels [3] and features of high harmonic generation such as cut-off, conditions for a plateau, and plateau height.

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Controlling Patterns and Turbulence in Nonlinear Optical Systems

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We show that by applying suitable optical feedback [1], derived from the spatial Fourier transform of the output electric field, we can control pattern formation and disorder in optical systems. We demonstrate the power of the method using various models of optical devices. First of all in a model of a Kerr slice with feedback mirror, we stabilise unstable patterns within a turbulent regime (panels (a) and (d) of the Figure). Secondly, we demonstrate the suppression of optical vortices in a broad area laser [2] (panels (b) and (e) of the figure). Finally, we show how the technique can be used to eliminate boundary effects on patterns in systems of finite width (panels (c) and (f)).

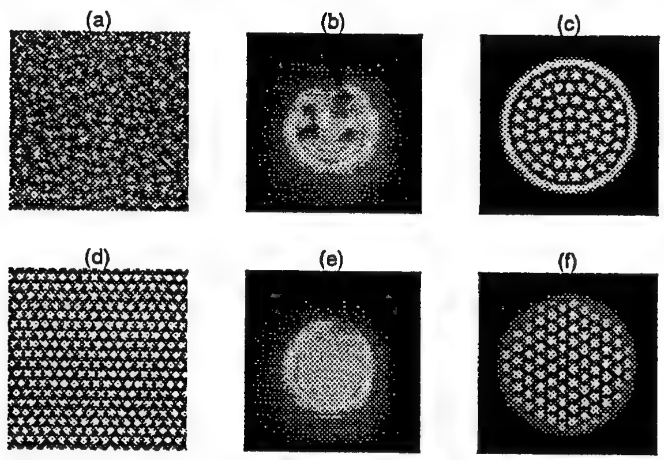

Figure 1: *The figure displays (a) turbulence in the Kerr slice model (b) optical vortices in a broad area laser and (c) a pattern of spots whose distribution is constrained by a circular boundary. (d), (e) and (f) display their respective controlled states after suitable feedback.*

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9. Industrial Application of Lasers

MICROPROCESSING APPLICATIONS

of

PULSED LASERS TO MANUFACTURING INDUSTRY

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During the past decade, excimer lasers have led the way in applying ablative material removal to micromachining applications in manufacturing industry. Recently short-pulse versions of more familiar industrial CO_2 and Nd:YAG lasers have also begun to be used for this application.

The ability to drill ever small holes - down to ~1μm diameter, is an underpinning technology in many industries which manufacture hightech products. For example, precision microdrilling with excimer lasers is now routine when making some of the delicate medical probes which measure *in situ* properties of blood in human arteries. The ~35μm diameter nozzle hole arrays in most of the ink jet printers currently sold in the world are now drilled by excimer lasers on production lines in Asia, Europe and the US.

In 1988 Siemens first productionized the use of excimer lasers for drilling 80μm diameter electrical feedthrough (via) holes in the multichip module (MCM) circuit boards that connect silicon chips together in high speed computers. Other mainframe computer manufacturers such as IBM rapidly followed suit and installed their own excimer laser based production lines for this application. In the interim period, trillions of vias have been drilled at yields of >99.99% with equipment whose mean time between failures (MTBF) has been logged at > 1,000 hours.

Recently it has been found that " non-thermal" ablation can also be achieved with less-expensive TEA and rf-excited slab CO_2 and Q-switched Nd:YAG pulsed infrared lasers. These sources are now used to drill precisly positioned vias at rates up to 200 holes/sec in other electrical interconnect package devices such as ball grid arrays (BGA's), tape automatic bonds (TAB's), flexible printed circuits (FPC's) and printed circuit boards (PCB's).

INDUSTRIAL LASER FACT FINDING MISSION TO JAPAN AND KOREA

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The uptake of laser technology into industry world-wide is currently very healthy, with growth in sales of laser materials processing equipment over the last few years running at around 10% per annum. The UK, however, continues to fall behind leading manufacturing nations in its uptake of this technology.

The Association of Industrial Laser Users was established in November 1995 to act as a focus for industrial laser activity in the UK. An important aspect of this work is the dissemination of information from research centres into industry.

Between 21 April and 2 May 1997 a team of seven representatives of the UK Association of Industrial Laser Users (AILU) undertook a DTI sponsored fact finding mission in Japan and Korea. The team, led by Professor Bill Steen (Liverpool University) visited key university, research institutes and industries in the two countries with the main objectives assessing new developments in industrial applications, evaluating best practice in industrial laser use and appraising techniques employed in the successful uptake of laser technology into industry.

The presentation will provide a brief overview of the mission findings but will concentrate on the role played by universities and research institutes in supporting industrial activity and the Japanese government's new Advanced Photon Processing programme.

10. Quantum Optics

WAVE PACKET DYNAMICS IN MOLECULES SUBJECTED TO INTERACTIONS WITH LIGHT

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The arrival of femtosecond laser pulses has heralded an era in which it is possible to interrogate molecular motion on a time-scale within a vibrational period and achieve state selection in molecular processes [1,2]. In this paper we have two aims: we will review some of our past theoretical work on the interaction of lasers with molecules in wave packet studies [2], and we will present new results concerning quantum beats and wave packets.

Some of our previous work placed an emphasis on the process of wave packet excitation and the traversal of a wave packet through resonances which couple it to another electronic level (known as a laser induced crossing). We use both simple models and exact quantum mechanical calculations performed on super-computers. We have also included the effects of spontaneous emission by both direct approaches and stochastic simulations of the density matrix evolution.

Quantum beats provide a useful tool in spectroscopy for the evaluation of fixed energy level differences. However, in wave packet dynamics the motion of wave packets about molecular energy surfaces provides time dependent energy differences. Thus a superposition of wave packets on two excited energy levels can yield quantum beats with a time dependent frequency that depends on the molecular dynamics [3]. We explore this problem with examples and simple models of wave packet quantum beats. The effects of separating wave packets, and wave packet dispersion, are of especial interest. Calculations are performed using a numerical integration of the time dependent Schrödinger equation with three energy levels and time dependent couplings. The effects of spontaneous emission are determined by using a fully quantum mechanical Monte Carlo wave function method.

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OPTICAL MEASUREMENT BY PROJECTION SYNTHESIS

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We present an extension of the projection synthesis technique proposed by Barnett and Pegg [1] whereby we determine the probability distributions of any physical observable of a quantised field mode. This has been realised by directly measuring a quantity proportional to the projection of the input pure state onto the eigenstate associated with the observable to be measured. It is found that we need to synthesise a specific reference state conditioned upon the property under investigation. We give a general expression for these reference states. We also address the problem as to whether these states can be fabricated [2]. We investigate homodyne detection using projection synthesis and form the family of probability operator measures (POM) required to characterise this measurement process. Furthermore, we shall utilize these results to form the POM and the Wigner function associated with a measurement scheme, introduced by Huttner and co-workers [3], used to distinguish between non-orthogonal coherent states.

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PHYSICAL IMPLEMENTATION OF QUANTUM ALGORITHMS

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Theoretical progress in recent years has indicated that a quantum computer may be capable of solving certain problems exponentially more efficiently than its classical counterpart. In particular, Shor's discovery of a polynomial time quantum algorithm for factorising numbers [1] has led to a significant increase in research, with a view to practical implementations of quantum computation. The major barrier from both an experimental and theoretical perspective is decoherence, whereby quantum coherence between qubits is destroyed due to coupling with external degrees of freedom.

We review the current status of this exciting new field. A *novel quantum algorithm* for a simple promise problem is introduced and two possible physical implementations, based on this problem, are discussed. The simplicity of this algorithm should allow experimental verification of the predicted entanglement effects.

In the first of these implementations, nuclear spins are used as qubits and magnetic resonance techniques are used to implement the logic gates [4]. In this case we consider a controlled-NOT gate as the basic building block of the quantum computer. In the second implementation photons are used as qubits and an optical Fredkin gate [5], which can in principle operate at the single photon level, is used to perform the logic. In conjunction with single bit operations these are universal sets of gates, in the sense that they can be used to approximate all unitary transformations to an arbitrary degree of accuracy.

The two implementations are compared, with emphasis on practical experimental difficulties and decoherence in each case. Nuclear spin systems have the advantage that decoherence times are large compared to many other possible implementations. The thermal relaxation time for a spin-1/2 nucleus can be several thousand seconds. In addition, implementation of the gates is based on mature experimental techniques. The advantages of using photon number states for quantum computing include weak coupling to the environment and ease of implementation of simple error correction schemes. The simplicity of mapping quantum computing algorithms onto known optical systems (eg. the ease of preparation of superpositions of states) continues to make optics an attractive option.

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Approximate construction of Quantum States using Superpositions of a few Coherent States

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Summary

A discrete set of coherent states on a von-Neumann lattice is well known to form an overcomplete basis in the Hilbert space. We use a finite sublattice ("truncated von-Neumann lattice") to construct quantum states, with a good accuracy.

The technique is demonstrated by constructing various quantum states (such as number eigenstates, squeezed states, Schrödinger cats etc.) as linear superpositions of coherent states on a truncated von-Neumann lattice. Numerical results show that the method is robust and very accurate. The accuracy is demonstrated with calculations that quantify the distance between the quantum state and its approximation (a) in the "x-representation" and (b) in the Wigner representation. The dependence of the error on the number and spacing of the coherent states is also investigated.

The method is a contribution in the general area of quantum state engineering.

MICROMASER CAVITY FIELDS AND THEIR QUANTUM MEASUREMENTS

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We have carried out a comprehensive numerical simulation of the dynamics of the ^{85}Rb atom micromaser [1] currently in operation at the Max Planck Institute, Garching, Germany [2]. We use matrix continued fraction methods accurate to one part in 10^{11} or better to solve the quantum dynamical equations of motion for one (or more [1]) 2-level atoms coupled to a heat-bath via a single resonant cavity field mode at finite temperatures $T < 0.5°K$ (and including [1] $T = 0.070°K$). In the experiments [2] the ^{85}Rb atoms enter the maser cavity in succession in the 63 $P_{3/2}$ Rydberg state, and the cavity is tuned to a transition to eg the 61 $D_{3/2}$ state at 21.506 GHz. The state of the quantised electromagnetic field created in the maser cavity, which can be either *sub*-Poissonian or *super*-Poissonian [1,2], is then measured by determining the states of the ^{85}Rb atoms after they have left the maser cavity.

We find that this *quantum measurement* process depends significantly, in general, on the efficiency ε ($0<\varepsilon<1$) of the ionisation detectors detecting the outcoming atoms in either of the Rydberg states. We find that for $\varepsilon \to 0$ (the regime previously investigated theoretically [1,3] and which corresponds to *zero* atoms actually detected), the microscopic dynamics, which is followed atom-by-atom for a cavity filled initially only with black-body radiation at temperature T (i.e. we start from thermal noise) can typically (but not necessarily) converge on the equilibrium Meystre formula [1-3] for the cavity field photon statistics found [4] by a *coarse-grained* dynamical analysis based on the Scully-Lamb laser equations. However, for $\varepsilon \to 1$, which means every outcoming atom is detected in one or other of its two states, results are very different. Typically the variance $v = [\langle n^2\rangle - (\langle n\rangle)^2/\langle n\rangle]^{1/2}$ for the cavity field photon numbers n is much reduced: indeed a super-Poissonian field ($v>1$) measured at $\varepsilon = 0$ becomes strongly *sub*-Poissonian ($0<v<<1$) for $\varepsilon = 1$: atom *detection,* which apparently reduces the Hilbert space available to the photons, thus has a substantial effect on the state of the maser cavity field. (Moreover, since atoms are detected *after* they leave the cavity there is apparently "action-at-a-distance" of an EPR-paradox-like kind between the atoms and the field.) However, when the "trapping state" condition [1] is satisfied we find the opposite: changing ε has a *negligible effect* for temperature $T \lesssim 0.070°K$, and a theoretical analysis in support of this conclusion will be presented.

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Entangled States and Novel Quantum Measurements

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Much attention has been given recently to the problem of enhancing the correlations between separated quantum systems using only local operations and classical communication[1,2]. Among the many interesting developments in this area has been the realisation by Bennett *et al*[1] that given a number of partially entangled states, one can, using only local operations, produce a smaller number of maximally entangled states. This procedure, known as *entanglement concentration*, provides a novel, highly non-classical way for distant users to share information, and may prove to be useful in fields such as quantum cryptography.

We elucidate a number of connections between the concentration of pure-state entanglement and two kinds of novel quantum measurement which have also attracted a great deal of attention in their own right, namely logically reversible measurements[3] and those which can be used to unambiguously discriminate between non-orthogonal quantum states[4,5]. Our examination of logically reversible measurements is motivated by the fact that entanglement reduction, using local operations and classical communication, can be carried out with unit fidelity. We show that there exists such an entanglement reduction scheme which is logically reversible, and can be physically reversed to give a local concentration protocol. This operation is, in turn, equivalent to the error-free state-discrimination measurement devised by Ivanovic[4] and Peres[5]. Finally, we show that when such measurements are employed to examine the correlations in the gedankenexperiment proposed by Hardy[6] and Goldstein[7] which demonstrates quantum 'nonlocality without inequalities', no violation of local-realism occurs.

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11. Visible Emission

OPTICAL FREQUENCY CHAIN AT NPL: PROGRESS AND PROSPECTS.

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We report progress at NPL towards an optical frequency chain inter-relating mid- and near-infra-red and visible optical frequencies. This project is motivated by the development of forbidden transitions in single cold trapped ions as optical frequency standards with stabilities potentially exceeding that attainable with microwave frequency standards. In particular, our group is studying candidate reference transitions in Sr^+ at 444.8 THz (674 nm) [1] and Yb^+ at 729.5 THz (411 nm), 642.1 THz (467 nm), and 87.4 THz (3.43 μm) [2]. Optical frequency measurements of these transitions are becoming limited by the Fabry-Perot wavelength comparison technique used to relate them to the iodine-stabilized HeNe reference.

The initial reference for the chain will be the methane-stabilized HeNe standard at 88.4 THz (3.39 μm), the frequency of which is known to 3×10^{-12} [3]. A transportable stabilized HeNe/CH_4 system is being constructed for NPL by the group of M.A. Gubin at the Lebedev Institute (Russia) and will be intercompared with frequency chains from Cs at PTB (Germany) and from CO_2/OsO_4 at LPTF (France).

The first step towards an optical-IR frequency chain is the generation of the 4th harmonic of the HeNe/CH_4 frequency at 353.5 THz (848 nm) in the near-IR. SHG of 3.39 μm radiation in $AgGaSe_2$ has been demonstrated with a conversion efficiency of 1.15×10^{-3}. The 1 nW power generated at 1.7 μm is insufficient for further SHG to 848 nm, and currently our approach to generate greater 1.7 μm power is by DFM of near-IR and green (515 nm or 532 nm) light. However, the advent of higher-power sources around 3.4 μm using parametric generation in PPLN may enable sufficient 2nd harmonic power to be generated to make direct SHG to 848 nm feasible.

The Sr^+ transition at 674 nm is close to the 5th harmonic of the HeNe/CH_4 frequency and can be accessed by DFM with 841 nm to generate 3.39 μm with the residual 3 THz mis-match being bridged by an optical frequency comb (OFC) in the near-IR [4]. Light at the Yb^+ 411 nm transition frequency is generated by SHG of a diode laser at 822nm. This system is an ideal testbed for the Hänsch-Telle optical frequency divider (OFD) scheme [5]. Using two OFD stages, the 848 nm - 822 nm frequency difference is reduced to 2.8 THz, which can be measured using the OFC.

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High Performance Oxygen-Free Solid-State Dye Lasers.

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Solid-state dye lasers (SSDLs) have the potential to be ultra cheap and simple pulsed laser systems tunable across the visible. They offer high commercial promise as low cost disposable lasers for high volume applications. Low cost is achieved by using a dye-doped polymer, a sol-gel glass or a sol-gel glass-polymer composite (polycom glass), which could be mass produced for only a few pounds per gain element. A pulsed pump source giving as little as 100 μJ in 10 ns is required along with a simple plane-plane cavity without the need for expensive or advanced low loss optical components. With the advance of diode pumping, the cost of a fixed wavelength pulsed laser pump source, such as an Nd:YAG laser at 532 nm or 355 nm, is constantly reducing.

Recent experiments were conducted on a state of the art polycom glass sample doped with perylene orange and pumped with a Nd:YAG laser (532 nm, 6 ns). Results show a threshold down to 53 μJ, a high slope efficiency of 72 %, and a normalised photostability, defined previously[1], of 50 $GJmol^{-1}$. The 120 shot damage threshold was measured as 26 Jcm^{-2} and no host matrix damage occurred after many thousands of pulses at 1.24 Jcm^{-2}. By utilising a sample rotation system as a convenient means gain material replacement and thermal load reduction, these results allow a prediction of 0.6 mJ/pulse for 6 million pulses (1 mJ pump) or 10 mJ/pulse for 2 million pulses (30 mJ pump).

Another very promising dye for SSDLs, pyrromethene 567, was found to photodegrade via a self sensitised photo-oxidation reaction[2]. Removal of oxygen from a pyrromethene 567 doped polymer matrix was found to improve photostability by a factor of six. Deuterated solvents, which increase the lifetime of singlet oxygen, accelerated photodegradation and sodium azide, a singlet oxygen quencher, stabilised the dye molecule. Singlet oxygen is, therefore, the most important species causing photodegradation of this dye.

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HIGH-POWER DIODE-BAR-PUMPED INTRACAVITY-FREQUENCY-DOUBLED ND:YAG AND ND:YLF RING LASERS

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The use of diode-pumped solid-state lasers as sources of high power visible light is an area which has attracted growing interest in recent years. This interest stems from the increased efficiencies available and compact size compared to Ar^+ lasers. A further attractive feature of intracavity-frequency-doubled, single-frequency lasers, on which initial results were recently reported,[1] is that axial-mode-hopping is suppressed. The explanation for this behaviour is based on the fact that adjacent (non-lasing) axial modes are further suppressed by an additional loss due to sum-frequency generation. This is twice the loss experienced by the lasing mode due to second harmonic generation. In a low loss resonator with efficient intracavity-frequency-doubling this extra loss can more than offset any gain advantage of adjacent modes closer to the gain peak. The net result is that continuous (mode-hop-free) tuning is possible over many axial mode spacings.

Here we describe an intracavity-frequency-doubled Nd:YAG ring laser end-pumped by a 20W diode bar, and a Nd:YLF ring laser end-pumped by two 20W diode bars. In each case, a simple bow-tie cavity design was employed, with a Brewster-angled LBO crystal. In the case of Nd:YAG for a non-optimised laser mode size in the LBO crystal the laser produced ~1.4W of single-frequency output in the green at 532nm. By varying the cavity length we obtained a single-frequency, continuous (mode-hop-free) tuning range of ~40GHz corresponding to ~80 axial mode spacings. This range is consistent with predictions of a simple model accounting for the effects of nonlinear loss due to sum frequency generation.

Nd:YLF offers the potential of an extended tuning range through its broader linewidth. Furthermore Nd:YLF is attractive for operation at higher powers due to its superior thermo-optical properties on the σ-polarisation compared to Nd:YAG, providing that appropriate steps are taken to avoid thermally-induced stress-fracture. Results for this laser, end-pumped by two 20W diode-bars, include the generation of ~10.3W of single frequency 1053nm output in a TEM_{00} beam ($M^2 < 1.1$), and ~6.2W of green output at 526.5nm (corresponding to ~8.5W generated internally in the LBO) and a conversion efficiency of ~5% with respect to intracavity power. We have obtained a single frequency, continuous (mode-hop-free) tuning range of ~72GHz corresponding to ~150 axial mode spacings. So far, the mode-hop-free tuning range has been limited by etalon effects due to imperfect AR coatings on the TGG Faraday rotator. With the elimination of these etalon effects, mode-hop-free tuning over a considerable fraction of the gain bandwidth should be achievable.

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THULIUM-DOPED UPCONVERSION FIBRE-LASER WITH 230mW OF 480nm BLUE OUTPUT

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Blue laser sources are required for a number of applications such as colour displays, printing and data recording. Three main approaches are currently pursued. Blue emitting laser diodes have recently been demonstrated[1], albeit with a number of limitations at present regarding power, lifetime and operating temperature. Another approach is frequency doubling of an infrared source; for example 49mW of 473nm light have recently been obtained by frequency doubling the output of a diode-pumped 946nm Nd:YAG laser in a single pass through a periodically poled LiNbO3 crystal[2]. The third approach is upconversion lasing, for which the highest reported power to date, at blue wavelengths, was 106mW from a diode-pumped Tm:ZBLAN upconversion fibre laser[3]. In this paper we report a blue output of up to 230mW, achieved by using a more powerful pump laser and a Tm:ZBLAN fibre with a modified composition, which has allowed higher power operation. Long term operation at the highest power is not yet possible however due to an optically induced loss in the fibre as observed in earlier work[3].

The pump laser was a Nd:YAG laser operating at 1123nm and pumped by a 7W diode-bar. This laser produced 1.6W in a circular Gaussian-beam of $M^2 < 1.1$. The high beam quality allowed overall launch efficiencies into the fibre of between 50 and 60%.

The Tm-doped fibre used, produced by Le Verre Fluoré, had a Tm concentration of 1000ppm (by weight), a N.A. of 0.2, a core diameter of 3μm and length of 2.2m. To form the cavity dielectric mirrors were dry butted against both ends of the fibre. The input mirror had high reflectivity for blue light, and a transmission of 90% for the 1123nm pump, which was launched through this mirror using an aspheric lens. The output coupler had a transmission of 37% for the blue. This laser had a threshold of 100mW of incident pump power, and a slope efficiency of 18.5%, again with respect to incident power. For high pump powers the slope efficiency rolled off, and the maximum output obtained was 230mW for 1.6W of incident power. It was noted that this output power could not be sustained. Instead, at a constant pump power, the output would gradually decrease to some sustainable level. Around 140mW was the highest sustainable power achieved. The underlying cause of this effect was an induced loss in the fibre at blue wavelengths, thus increasing the threshold and decreasing the slope efficiency. Further tests revealed that this loss is not permanent and it can be entirely removed by operation of the fibre laser at low powers for a time of the order of an hour. It is hoped that an understanding of the loss mechanism and it's relation to material composition could lead to upconversion lasers with even higher sustainable powers.

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HIGH AVERAGE POWER BLUE GENERATION FROM A COPPER VAPOUR LASER PUMPED TITANIUM SAPPHIRE LASER

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Generation of multi-watt blue output at high pulse repetition frequency (PRF) is required for applications such as large area full colour laser projection television systems. We have developed an efficient blue laser based on a frequency doubled Ti:sapphire laser pumped by a very high beam quality copper vapour laser (CVL).

The CVL system consisted of a small scale (3 W) master oscillator and a double pass amplifier and gave up to 18 W of near diffraction limited green and yellow (510.6 nm and 578.2 nm) output at 6.2 kHz PRF. Using this CVL system it was possible to efficiently pump a 10 mm long 0.15% Ti:sapphire crystal without experiencing the crystal damage problems previously encountered in CVL pumped Ti:sapphire lasers. In the present work, the CVL beam was focused through the Ti:sapphire crystal to produce a waist 15 mm beyond the crystal using a 1.65 m focal length mirror thereby producing a ~300 μm diameter pumped region.

When the Ti:sapphire laser was operated with a standard Z-cavity (shown dotted in the figure), a maximum broad-band output power of 6.2 W (44% slope and 32% absolute efficiencies) was obtained. Narrowband operation at 780 nm was achieved using a low power (10 mW) cw diode to seed a ring cavity, and gave 4.8 W narrowband output. For generation in the blue by frequency doubling however, the Ti:sapphire laser needed to be tuned out to ~920 nm where low power diode seeding alone is not sufficient to force narrowband operation. Insertion of four intracavity Brewster prisms enabled efficient (up to 20% absolute efficiency, 57% slope efficiency) operation at 920 nm with low enough bandwidth (~1 nm) without seeding to enable efficient frequency doubling into the blue. Using a 15 mm long intracavity LBO crystal, blue output powers of up to 1.8 W were generated (sum of both propagation directions generated within the standing wave cavity) corresponding to 10% conversion efficiency from the blue output.

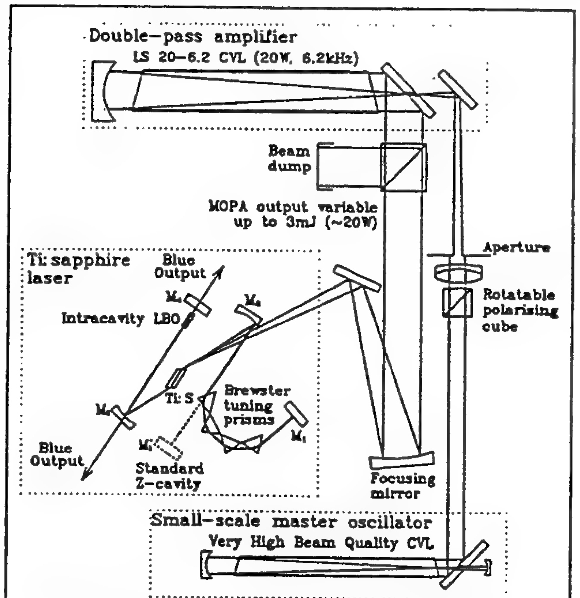

Figure 1 Layout of the CVL MOPA pumped Ti:sapphire laser with intra-cavity frequency doubling.

RED, GREEN AND BLUE INTRA-CAVITY DOUBLED MICROCHIP LASERS

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Microchip lasers are typically formed by applying dielectric mirrors directly to two near-parallel surfaces of a thin slice of laser gain material. Nd^{3+} is a commonly used active ion with its main transitions from the $^4F_{3/2}$ level occurring at 0.9um, 1.06um and 1.3um. Lasing of all these transitions, by diode-pumping of Nd^{3+} lasers around 810nm, has been demonstrated by numerous groups. Microchip lasers, based on the 1.06 and 1.3um transitions, have been demonstrated in various Nd^{3+} doped materials.

We have observed monolithic Nd:YVO_4 devices to have low thresholds (17mW at 1342nm, 12mW at 1064nm) and high slope efficiencies (48% at 1342nm, 51% at 1064nm) in a TEM_{00} mode from laser diode pumping. The maximum single frequency power at 1342nm (5% output coupling) was 84mW, with 120mW obtained at 1064nm (10% output coupling) being limited by the pump power available. The threshold for the 913nm transition in Nd:YVO_4 is prohibitively high to allow efficient diode-pumping in a monolithic geometry, though lasing has been observed producing 2mW of output power for 1W of pump power. Nd:YAG, with a higher terminating level, and less reabsorption, was therefore chosen as the gain material for examining this transition.

These fundamental transitions can be frequency doubled to produce red (671nm), green (532nm) and blue light (473nm) using Nd:YVO_4 & LBO, Nd:YVO_4 & KTP and Nd:YAG & $KNbO_3$ respectively. We have shown green devices can produce 132mW with 650mW from a laser diode [1], and 33mW of blue from 1W of pump power [2]. Preliminary results with the red devices have shown more than 10mW of red for 750mW of pump power.

The use of short non-linear crystals in these devices, combined with their small cavity length, can lead to a polarised, stable intensity output. A full description of the frequency and intensity stability of these devices will be given, with comments on the scalability of these devices and applications.

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WORKSHOP SESSION

Resonant Cavity Light Emitting Diodes

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The generic structure of a resonant cavity light emitting diode consists of light generating quantum wells located inside an optical cavity defined by two reflectors. Usually one of the reflectors is a distributed Bragg reflector whose reflectivity is determined by the number of periods it comprises and the other is a high reflectivity metal mirror. Apart from the metal mirror, the entire structure is formed by epitaxial growth of semiconductor layers so the optical cavity is usually only a micron or so in length. Typically, the structure will contain 3 quantum wells located at an antinode of the electric field in the structure and the number of periods in the Bragg structure can vary from 2 to 16. The structure clearly resembles the vertical cavity surface emitting laser but the reflectivities of the mirrors are not high enough to allow lasing action and spontaneous emission dominates.

The devices are interesting because the micro-cavity influences the optical linewidth, peak spectral power density and angular distribution of the emitted radiation. Changes in these factors might be expected on simple physical arguments but there are often subtleties which are less obvious but significant. The observed enhancement of the efficiency was probably not anticipated but it is this factor which is perhaps the most interesting. The efficiency of conventional LEDs is dependent on carrier injection efficiency, internal quantum efficiency and extraction efficiency, that is the fraction of light which can be transmitted through the semiconductor surface. The high refractive index (3-3.5) of the semiconductor material prevents most of the light leaving the material, instead reflecting it back by total internal reflection at the air-semiconductor interface, hence limiting the extraction efficiency of the device. The resonant cavity modifies the angular distribution of emission in such a way that a much larger fraction of the emitted light falls within the critical cone angle and is able to leave the device, thus substantially enhancing the device efficiency.

We will review the development of the microcavity LED showing results on InGaAs/GaAs quantum well devices emitting at around 960nm and some recent results on InAsP quantum wells emitting at around 1350nm. Evidence of linewidth narrowing, enhanced peak powers emission and efficency (at 960nm) will be presented. Recent results on high speed switching will also be presented and designs offering possible further enhancements in switching speed will be discussed.

Spontaneous emission lifetimes and four-wave mixing in III-V microcavities

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Semiconductor microcavities have shown remarkable effects on the spontaneous light emission properties of free carriers(1) and on the physics of coupling between photons and exciton polaritons(2). The first effect is important for LEDs at room temperature where the coupling to the cavity is weak. The second is mainly important at low temperatures and densities where excitons can exist. In this paper we are primarily interested in the dynamics of both of these regimes, in particular in the effect of the cavity on spontaneous lifetimes and in the effect of inhomogeneous broadening of excitons on dephasing of the cavity polaritons.

Microcavity LEDs have shown remarkable advances over the last 3years, particularly in quantum efficiencies. Planar MCLEDs consisting of InGaAs/GaAs quantum wells in a cavity with a metal/Bragg mirror combination have given up to 23% external quantum efficiencies(1). Along with this, directionality and spectral content can be engineered. It has been suggested that such high efficiencies in planar geometries are partially due to photon recycling of light emitted into the lateral guiding modes of the cavity. Such recycling would increase the spontaneous emission time and degrade the device bandwidth, a parameter of vital importance for applications. We have made a detailed study of the bandwidth properties of a series of microcavity and nonmicrocavity LEDs of different sizes and at different current densities using the small signal approach. We show that no degradation of bandwidths is evident up to LED sizes of 80 micron. We also show that small bandwidths up to 1 GHz are possible for these quantum well LEDs. It seems that high efficiencies can be obtained without degradation in the time domain.

In the case of strong coupling, achieved with a combination of high finesse cavities and by increasing the number of wells, the key signature is vacuum Rabi splitting of the coupled modes, Rabi oscillations, and the emergence of 'cavity polaritons'. The nature of the broadening of the bare exciton resonance plays an important role in determining how the coupled states evolve in time and in particular how they lose their coherence. In the case of homogeneous broadening, the coupled states are equally photon and exciton-like so that the dephasing time will be correlated with the cavity lifetime in the case that phonon processes are relatively slow. In the case of inhomogeneous broadening on the other hand, the situation is much more complex so that the exciton and photon contribution to the coupled states can change and hence the dephasing can also change. We have measured the dephasing times in a series of samples with varying cavity lifetimes and inhomogeneous broadening and show the evolution in times as a function of both of these parameters.

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New developments in research on photonic microstructures based on epitaxial III-V semiconductors

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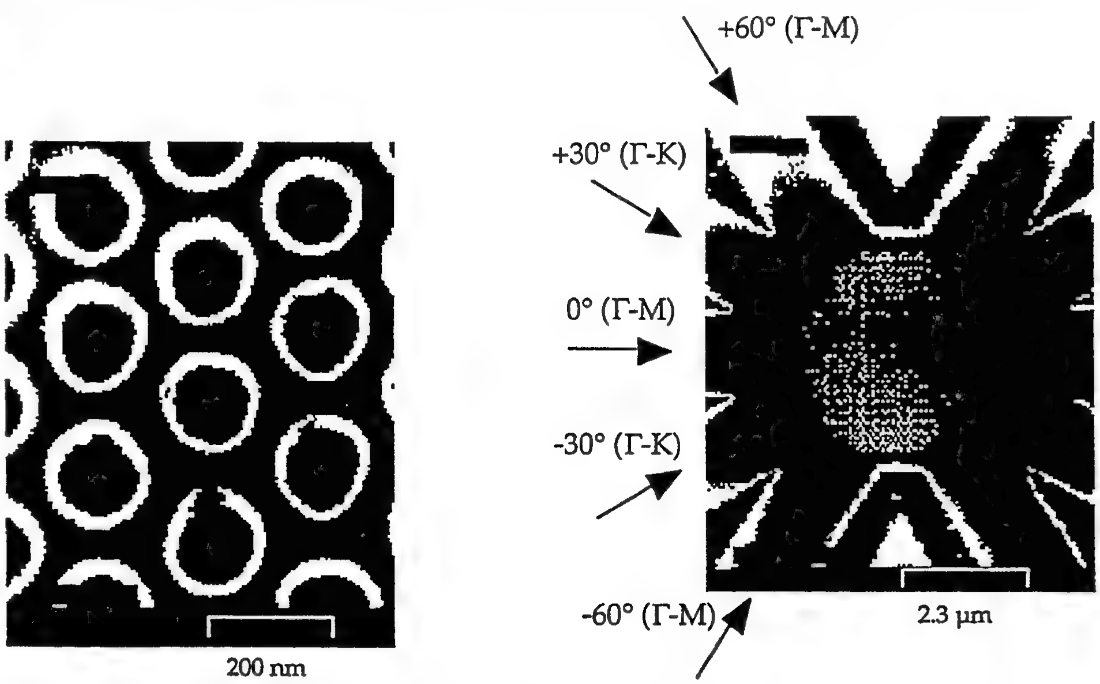

Figure. 1: Scanning electron micrographs of III-V waveguide photonic microstructure (Ref. 6).

This paper gives an outline review of work on photonic microstructures carried out by members of the Optoelectronics Research Group at Glasgow University and supported by the Nanoelectronics Research Centre and Dry Etch Research Group. But the work described has involved a number of collaborations,

both national and international - and this collaborative dimension is recognized in the list of authors above.

Work on the fabrication of photonic microstructures using our leading-edge electron beam lithography (EBL) (Leica EBPG5 Beamwriter) and dry-etching capabilities has been reviewed elsewhere(1-3). Experiments demonstrating that the 1D and 2D photonic microstructures (see Fig. 1) which we have fabricated in epitaxial III-V waveguides genuinely show photonic bandgap and microcavity effects have also been described thoroughly in the literature(4-10).

Epitaxial III-V semiconductors have the potential to provide 21/2D and fully 3D photonic microstructures which exhibit the desirable combination of intrinsically very efficient current-injection electroluminescence and complete control/inhibition of the spectral and angular characteristics of the spontaneous emission process. We have previously reviewed the technology armoury associated with epitaxial III-V semiconductors(2) and concluded that 'all-solid' device structures are feasible if techniques such as selective oxidation of high Al-content $Al_xGa_{1-x}As$ (or other analogous Al-compounds) and quantum well intermixing (QWI) are exploited. Our recent work on these techniques will be reviewed. For photonic microstructures, the primary importance of selective oxidation is the large refractive-index contrast which it produces directly in an already grown epitaxial structure. But the insulating nature of the oxide has already been shown to have a powerful impact on the threshold current of lasers(11). The primary point to be made at this stage is that the selective oxidation process can be modulated in all three spatial dimensions via a suitable combination of epitaxial growth, masking, dry-etching and other processes. Selective oxidation also has an obvious role to play in waveguide-based photonic microstructures.

The advent of GaN-based blue LEDs and lasers has produce a rapid expansion in research and has already made a major impact commercially. We shall review, briefly, new work on dry-etch processing of patterned structures in GaN layers grown epitaxially on sapphire substrates(12,13). This work is a preliminary stage in the development of photonic microstructures (and even nanostructures) in epitaxial semiconductors suitable for visible and even uv wavelength operation.

Epitaxial semiconductors, albeit within the very different framework provided by synthetic opal, also show strong evidence of photonic bandgap effects in both their photoluminescence behaviour and their passive transmission and reflection properties. Several different semiconductors, both III-V and II-VI, have already been investigated. Because of the nature of the self-organised large-'domain' periodic, silica-ball structure of the opal host, the material resulting from the epitaxial deposition process is significantly inhomogeneous, with only partial filling of the voids by the semiconductor. This situation implies that the refractive index contrast may be sufficiently large for full 3D photonic bandgap effects to be produced, even though the structures must have a substantial level of irregularity. Recent results from our joint work will be described(14-17).

We also mention a forthcoming tutorial review(18) and possibly the first definitively photonic microstructure-based waveguide laser(19).

Finally, brief reference will be made to the possibility of observing useful nonlinear behaviour in photonic microstructures. We believe that there are many interesting possibilities for nonlinear effects in photonic microstructures. Grating coupling coefficients ('kappas') which can be chosen within a wide range of values (i.e. from below 10 cm^{-1} to several 1000 cm^{-1}) and the localisation possibilities of phase-shifted microcavities, in 1D and 2D, add up to fertile territory for nonlinear effects such as gap solitons.

Acknowledgements

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PHOTONIC CRYSTAL WAVEGUIDES

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It is now widely recognised that a volume of dielectric material with an appropriately designed periodic micro-structure – a *photonic crystal* – will support a full three-dimensional photonic band gap. Over the frequency range spanned by the gap, all electromagnetic modes are suppressed within the volume, allowing a single resonance (or photonic state) to be introduced by means of a structural point defect. This unique ability to tamper strongly with the electromagnetic mode density enables the channelling of spontaneous emission into one or a few electromagnetic modes, and is attractive for enhancing the emission rate from light emitting diodes, and in achieving low threshold highly efficient operation in micro-cavity lasers.

Although photonic crystals with full photonic band gaps at optical frequencies seem likely to have a revolutionary impact in optoelectronics, they are not yet available, largely because the technological demands on nano-fabrication challenge the current limits of the state-of-the-art. There is, however, much more to photonic crystals than a full photonic band gap. For instance, silica photonic crystal fibres (whose cross-section consists of a periodic array of sub-micron capillaries and whose core is a missing capillary) guide light in novel ways, exhibiting very unusual properties; they can be strictly single mode at all wavelengths of excitation. This turns out to occur because of the peculiar properties of total internal reflection at a photonic crystal.

Thin film waveguides (of III-V semiconductors, for example) etched through with periodic arrays of air holes can, if suitably designed, guide no modes within the frequencies spanned by the photonic band gap (a momentum gap prevents the formation of transverse resonances across the guiding layer). This use of photonic band gaps is being actively pursued in the context of vertical cavity surface emitting lasers, where in-plane gain can seriously reduce the overall vertical emission. In a slightly different version of the same idea, all but one mode of a multimode waveguide can be eliminated, which may prove useful in high power single-transverse-mode waveguide lasers.

Photonic crystal waveguides can also be designed to support high finesse *stationary* modes, i.e., modes which are localised at one point in the waveguide. This can be done either by operating at a band edge (zero group velocity in the plane) or by creating a mid-momentum-gap resonant state by means of a point defect.

In summary, there are almost as many reasons for using photonic crystal waveguides as there are ways of designing them. In the talk I shall discuss several examples, paying particular attention to their potential in applications.

POSTER SESSIONS

1. Optical Physics

MICROWAVE INDUCED QUANTUM JUMPS IN A SQUID RING

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Abstract
This paper is concerned with the interaction of a monochromatic microwave source with an ultra small capacitance SQUID ring, i.e. a Josephson weak link enclosed by a thick superconducting ring of geometric inductance Λ. From the viewpoint of quantum optics what is of particular interest in this system is that the ring-field interaction energy can easily be comparable, or larger than, the minimum separation between the energy levels of the ring. This means that even for microwave fields of very modest magnetic flux amplitude, this system is highly non-perturbative so that coherent multi-photon absorption processes tend to dominate. Thus, it is possible to induce transitions between SQUID ring states even when the microwave frequency is very small ($\approx$ 5%) compared with the separation in frequency units between the ring energy levels. As we demonstrate, for experimentally realisable SQUID rings, it is sufficient to adopt a two level description of a ring. This, in turn, has made the problem of solving the time dependent Schrodinger equation for the ring in a microwave field tractable. In this paper we present numerically computed solutions of the TDSE for the system which reveal quantum jumps at specific values of the static magnetic flux applied to the ring. We show that these jump regions in a microwave-driven SQUID ring can be probed by radio frequency (rf) techniques. We provide experimental examples taken using ultra small capacitance niobium point contact SQUID rings in a very low noise environment.

QUANTUM OPTICS OF LOSSY BEAM SPLITTERS

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Beam splitters are vital components in many optical experiments. Examples include interferometers, measures of coherence, and the investigation of nonclassical effects such as antibunching, squeezing and two-photon interference [1]. In quantum optics little attention has been paid to the properties of lossy beam splitters as they tend to supress any nonclassical behaviour. There are, however, nonclassical effects which depend upon medium losses [2], so the lossy beam splitter deserves some consideration.

In this paper the familiar input-output relations for an optical beam splitter [3] are generalised to allow for linear absorption by the medium forming the mirror. An essential feature of the model is that, in order to preserve the field commutators, the loss necessarily introduces noise into the system [4]. This has consequences if one of the inputs is squeezed, as this noise will necessarily be at least as noisy as a standard vacuum. This effect becomes particularly apparent if the beam splitter is used in a homodyne detection system. It causes a reduction of the amount of squeezing measured. We also report on an unusual novel two-photon interference effect [5], which can lead to apparent nonlinear absorption. At its most marked either both photons are absorbed or neither of them is. It becomes impossible for just one to get through.

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BLACK-BODY RADIATION DESTROYS COHERENCE INDUCED IN THE MICROMASER CAVITY FIELD

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Slosser and Meystre [1] have described the creation of exotic pure states of the micromaser cavity field by causing incoming two-level atoms to enter the cavity in the coherent super-position state $|\psi\rangle$, $|\psi\rangle = \alpha|e\rangle+\beta|g\rangle$; $|\alpha|^2+|\beta|^2 = 1$, of their 'excited' states $|e\rangle$ and 'ground' states $|g\rangle$. These exotic states have zero entropy $S = 0$ (pure states) and are reached as the number N of atoms successively entering the maser cavity $\rightarrow \infty$ i.e. $S \rightarrow 0$ as $N \rightarrow \infty$. Some of these states can be seen as "macroscopic superpositions" of suitable disjoint (unconnected) cavity-field states and exemplify Schrödinger-cat-like states. The calculations assume an ideal cavity, $Q=\infty$; and the trapping state conditions for n-photon cavity field states $|n\rangle$, namely $\sqrt{n+1}\, gt_{int} = r\pi$ (r = suitable odd integer) (in which g is the atom field coupling and t_{int} is the time during which the atom is inside the cavity), play an essential role in determining these particular final field states.

Previously [2] we have developed matrix continued fraction numerical methods to solve essentially exactly for the dynamics of the "real" micromaser for which the cavity has a $Q < \infty$ ($Q \sim 3 \times 10^{10}$ [3]) and is coupled to a heat-bath at a finite temperature T (0.5°K>T > 0). In these simulations all atoms enter in $|e\rangle$ ($\beta = 0$) as in the experiments [3]. We have now extended these calculations to include atoms entering, successively, coherently in $|\psi\rangle$ ($\alpha,\beta\neq 0$). Because the density matrix ρ for atom plus field *at the finite temperature* T is still coupled only along diagonals (but now both on *and off* the main diagonal) we are able to solve the system by the same numerical methods. We can then compare our 'exact' results obtained similarly for $Q=\infty$ (but $T>0$ as in [1]) with our 'exact' results for $Q < \infty$ (and $T > 0$); and we can compare each of these against the results reported in [1]. These are ongoing calculations; and, because we must cover the whole of the cavity field Hilbert space, are time consuming even with Manchester's IBM Computer Intensive Facility. However, and despite evidence to the contrary [4], it is already plain that, while trapping states can continue to dominate the dynamics, finite temperatures (T=0.5°K) dramatically change both the cavity field evolution and the final equilibrium state as compared with the exotic states, that is with tangent and co-tangent states, reported in Refs.[1]. Our paper will present the results of these numerical investigations as achieved by September 1997. (Note: When $Q = \infty$ but $T>0$ the cavity field is *initially* a (truncated) black-body field as was chosen in [1].)

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SIMULATIONS FOR TEACHING ADVANCED LASER PHYSICS

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Accurate simulations of processes associated with laser physics have been used for many years in the research community. These simulations were often written in-house, and were aimed at those who already had an expert knowledge of the field. However, variants of these sorts of simulations can be a valuable aid to those attempting to achieve a conceptual understanding of the topics involved, and also to come to terms with the complexities of our subject. We report and will demonstrate a number of simulations that we have written to support our teaching of undergraduate and postgraduate courses in laser physics and related topics.

Simulations of a particular topic can assist the learner by giving an immediately visual picture of what some section of theory means. Even if a particular equation may be easily interpreted by an expert in the field, it can benefit the learner to see how the end results change as input parameters are varied. The focussing of a gaussian beam is one such simulation. The result of passing a gaussian beam through a positive lens is easy to calculate, but few beginning students will have much of a feel of what happens to the focussed beam spot size and longitudinal position as the characteristics of the input beam are changed. This is readily performed graphically, and compared with "conventional" geometrical optics.

Where simulations become even more important is in the solution and display of the results associated with sets of equations for which there is no general analytical solution. The modelling of relaxation oscillations / gain switching is one such situation. Another is the role of gain saturation in laser amplifiers. Both of these topics are addressed in our suite of programmes, and allow the student (and practising scientist!) to explore what happens as various changes are made. We will also present simulations we have written that allow the exploration of (i) three wave mixing and its relevance to optical parametric oscillators, and (ii) coherent processes in atoms such as Rabi flopping and electromagnetically induced transparency. These will be available for attendees to work with at the poster.

The background material necessary to allow the student to make best use of these programmes is presented by a Web browser. Links from this then start up the relevant simulation. We have developed both the background and the simulations bearing in mind that the student should find these as easy to drive as possible, and that the results should be presented in as immediately obvious a way as possible.

The current system runs on a PC. Its development has been supported by the Scottish Higher Education Funding Council, through a collaborative initiative between Heriot-Watt and St Andrews Universities.

Topological Features of a Trapped Cold Ion

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It is anticipated that limiting the kinetic energy of an ion confined to move in two dimensions within a trapping potential will exhibit the peculiar Fermion-like characteristics of pure Chern-Simons theory. [1] Such novel features, whose inherent cause is the topological nature of the Chern-Simons interaction, should in principle be detectable using the techniques of trapped-ion spectroscopy.

We consider an ion whose motion is confined to a plane perpendicular to a constant magnetic field. An harmonic trapping field is applied within the plane of the ion's motion, together with a irradiating probe beam. Although conceptually simple, such a configuration has a rich fundamental structure.

By determining the dynamics of the ion we show that the particle theory is formally equivalent to that of a coupled massive $(1+2)$-dimensionsal vector Boson field. The field characteristics of current and Proca mass take on the rôles of the interaction Hamiltonian and harmonic potential respectively of the ion, while the topological mass appropriate to the restricted configuration space, which in the case of the vector Boson field is given by the Chern-Simons term, is provided by the constant magnetic field. Unique and potentially useful features of the ion's wave functions in the low kinetic energy regime are presented, where a decoupling of the eigen energies appears to occur.

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Investigation into photostimulated luminescence in BaFBr:Eu^{2+}

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BaFBr:Eu^{2+} plates are commonly used in radiography as a reusable imaging device for X-rays. The mechanisms for excitation, storage and optical interrogation of the phosphor are still controversial, but it is generally understood that F-centres and "hole-centres" are stored separately and gain their stability by spatial separation, but recombination may be induced by photo- or thermal stimulation leading to luminescence.

Samples synthesised at Edinburgh University, of powdered BaFBr with 0.1at% added europium, were irradiated at room temperature using Cu Kα X-rays and the luminescence detected with a photomultiplier. White light filtered by a monochromator, or 639nm diode or 543nm helium-neon lasers, were used as stimulation sources.

The stimulation spectrum is found to be sensitive to the preparation of the phosphor material, in particular the annealing prior to irradiation. The change in response by annealing at various temperatures and under different chemical atmospheres is reported, and interpreted as preferential formation of F-centres on F^- and Br^- sites. These may be separately interrogated by using red and green lasers. The implications for models of defect formation and recombination by quantum-mechanical tunnelling are discussed.

This work has been supported by BNFL under Agreements A709393 and A709548 and by UK EPSRC with an award of a Studentship to M. Bradford.

Co-existing Conservative and Dissipative Behaviours in a Coupled Laser Model

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In this presentation we model the dynamical behaviour of the simplest array of coupled Nd:YAG lasers, that is two lasers in a parallel configuration [1]. The system may be modelled via rate equations obtained by adiabatically eliminating the material polarisations from the Maxwell-Bloch equations (single-mode class-B lasers). In the resulting set of coupled ordinary differential equations, interaction between the two lasers via evanescent overlap is accounted for by a real coupling parameter K, its magnitude being governed by the coupled laser geometry.

It is a commonly held belief that a real constant K corresponds to purely dissipative coupling of the lasers. In order to understand the role played by the coupling, we have neglected the (small) dissipations due to spontaneous emission. The resulting rate equations are dynamically reversible with a flow divergence which is, in general, non-zero and time dependent.

By studying the behaviour of the phase difference between the two lasers, via an effective coupling parameter $2K/\Delta$, where Δ is the relative detuning, we can track down the parameter region most likely to display coexistence of conservative and dissipative behaviours of the kind described in [2]. A numerical analysis shows that for $2K/\Delta \lesssim 1$ the system's dynamical nature (i.e. conservative or dissipative evolution) depends crucially upon the choice of initial conditions. Further, we show that conservative dynamics is commonplace in the coupled laser model, thus invalidating the belief that real values of K always lead to dissipation. For example figure 1 shows Poincaré section crossings generated by conservative orbits and figure 2 shows the quasi-periodic variation of the intensity in time expected for conservative behaviour.

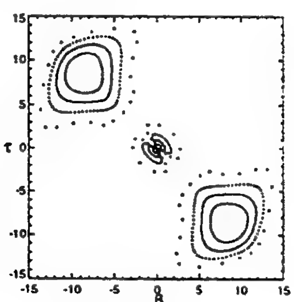

Fig. 1

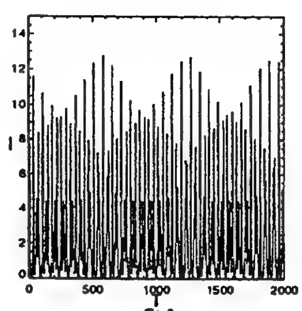

Fig. 2

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Giant Excitonic Polarization Rotation in Linear Reflection from ZnSe

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We report the first observation of gyrotropic linear dichroism near excitonic resonance. Gyrotropic linear dichroism is an effect of optical non locality. In cubic crystals of the zinc-blend symmetry it manifests itself as birefringence and dichroism linear in the light wave vector k. In crystals of zinc-blend symmetry, for light propagating along the cubic axis [001] the crystal eigenwaves are linearly polarized along [110] and $[1\bar{1}0]$: the main dielectric coefficients are $\epsilon_{1,2}(\omega) = \epsilon(\omega) \pm ik\gamma(\omega)$, respectively. Here γ is a measure of non-locality. Such birefringence results - in particular - in a polarization plane rotation for light reflected normally from a crystal surface. Recently, a rather small rotation due to this effect has been observed and associated with the lack of time-reversibility in the interaction of light with crystals showing non-local response. We decided to explore this important finding by examining gyrotropic linear dichroism near excitonic resonances. Optical non locality is known to be a very important feature of the optical response of excitons and therefore much stronger polarization effect may be anticipated. In this paper we report that gyrotropic linear dichroism in ZnSe appreciably grows in the proximity of an excitonic reflection resonance.

We perform our experiments close to the Γ_8-Γ_6 exciton resonance of a high-quality epitaxial ZnSe crystal of thickness 1.2μm which was grown on a ZnSe substrate oriented in the [001] direction. The sample is kept at 6K during all measurements. No heavy-light hole splitting can be observed in excitonic reflection spectra which shows virtual absence of stress in the ZnSe layer. We use a frequency doubled Ti:Sapphire laser producing picosecond pulses as optical source.

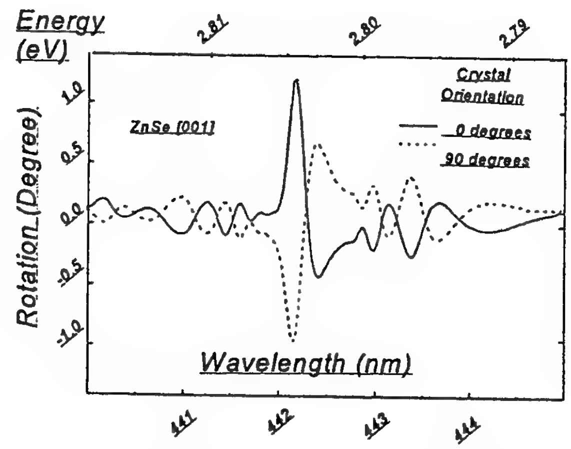

Figure : Polarization azimuth rotation for linearly polarized incident light versus wavelength in reflection.

Figure shows the polarization azimuth rotation for linearly polarized incident light versus wavelength in reflection for two different crystal orientations. A rotation that exceeds one degree is clearly observed close to the excitonic resonance. The dependence of the rotation angle on crystal orientation in the maximum of rotation (λ=442.2nm) accurately matches the predicted dependence for gyrotropic linear dichroism. From our experimental data the non-locality parameter γ can be measured directly: $Im\{\gamma/(\epsilon-1)\} = 7\times10^{-8}$ cm at $\lambda = 442.2$nm. We believe that the observed resonant polarization rotation can be attributed to the presence of electron-momentum linear terms in the exciton dispersion. Therefore, the effect of gyrotropic linear dichroism can be used as a new type of exciton spectroscopy. The size of the effect as well as its sensitivity also makes it potentially valuable as a diagnostic tool to determine cubic crystal orientations. If the effect is developed into an imaging technique the domain structures of epitaxially grown samples may be readily observed.

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Gyrotropic Linear Dichroism and Broken Reversality of Light-Matter Interactions

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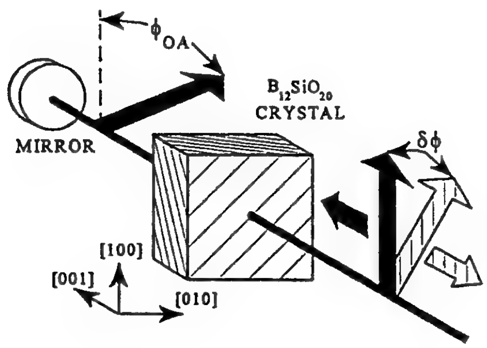
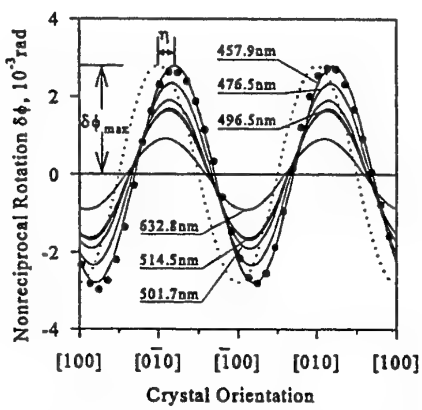
It was a common belief that the interaction of light with a nonmagnetic media was time reversible and that polarization-sensitive light-propagation effects were reciprocal. This reversality was recently questioned for various nonlocal optical interactions such as the transmission of light through the border with a chiral media, for the propagation of light in zinc-blend crystals, for reflection from an antiferromagnetic material with zero net magnetization, and, more generally, for the interaction with media lacking an inversion centre.

We report the first observation of nonreciprocal gyrotropic linear dichroism, in a crystal having 23 point group symmetry, which indicates broken reversality of the light-matter interaction, and on the theoretical concept of lack of reversality in nonlocal light-matter interactions [1-2].



Schematic of the experiment for measurement of nonreciprocal polarization rotation $\delta\phi$ in the optically active crystal $B_{12}SiO_{20}$, which has 23 point group symmetry.The single pass polarization rotation ϕ_{OA} is only partially compensated for when the light wave returns through the crystal. The magnitude and direction of $\delta\phi$ depends on the angle ϕ of the incident polarization.



Dependence of the nonreciprocal component of the polarization azimuth rotation $\delta\phi$ on the polarization azimuth ϕ of the incident light wave as the crystal was rotated around the [001] direction. For clarity, the experimental points are only presented for $\lambda = 457.9$nm, measurements at all other wavelengths are represented by lines of best fit. The oscillatory dependence observed, offset by η with respect to a *cos(2ϕ)* function, agrees with predictions in [1].

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Cubic Optical Nonlinearities of Metals in the Vicinity of the Melting Point

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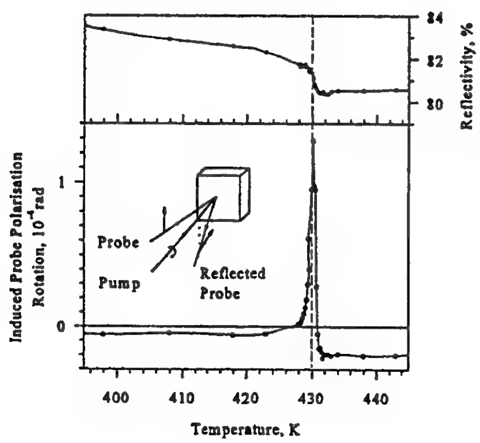
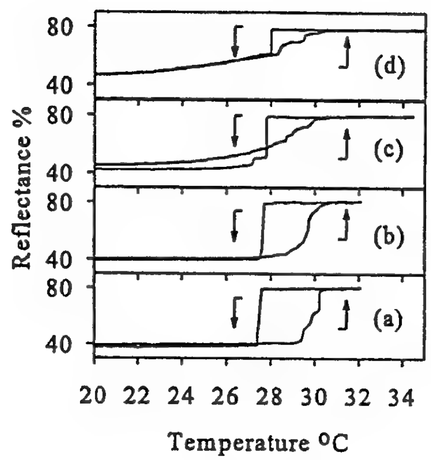
We report the first study of frequency degenerate cubic optical nonlinearities in bulk metals across the melting point. Using pump-probe reflectivity and precise pump-probe polarimetry a strong, femtosecond, electronic nonlinearity ($\chi^{(3)} \sim 10^{-8}$esu) has been observed in indium. The effective nonlinearity sharply increases when the temperature approaches the melting point. An even larger thermal nonlinearity ($\chi^{(3)} \sim 10^{-1}$esu) has been observed in the reflection hysteresis of gallium undergoing transitions from solid to liquid and back to solid.



Temperature dependance of the reflectivity and the probe polarization rotation due to the Specular Inverse Faraday Effect (SIFE), in indium across the melting point. A schematic of the SIFE is shown.



Pump-probe experiment on the temperature dependance of gallium reflectance across the melting point:
a) with probe beam only,
b) with pump at $2kWcm^{-2}$,
c) with pump at $7kWcm^{-2}$,
d) with pump at $12kWcm^{-2}$.

We also report on results of a study on the nonlinearity of nickel films and discuss the effect of an interface with glass on the magnitude and sign of the nonlinearity.

2. Microcavities and Photonic Bandgaps

EXPERIMENTAL CHARACTERISATION OF EFFICIENT POROUS SILICON LIGHT EMITTING STRUCTURES DESIGNED USING A PHOTONIC BAND GAP APPROACH

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It has recently been shown that periodic microstructuring of porous silicon to introduce photonic band-gap effects can radically change the optical mode densities in devices, and potentially the exciton lifetimes, resulting in enhanced performance[1].

To optimise the output available from periodically structured porous silicon, a computer program has been developed to model electromagnetic field propagation in device structures. This model accounts for the effects of dispersion, emission and absorption within arbitrary sequences of porous silicon layers that have different thicknesses and degrees of porosity[2]. Recent work has examined the emission from high porosity (low index) regions in single layers, multilayer stacks and microcavities.

We present, for several periodic porous silicon structures, a comparison of experimental findings with the modelled results and show that despite high absorption in the low-porosity layers, the emission in a multilayer stack and microcavity can be considerably enhanced over that of a comparable single low index layer. Results also demonstrate the importance of angle-resolved measurements to fully characterise the samples.

Fig.1 below shows the excellent agreement in the fit between theoretical modelling and experimental measurement of the passive reflectivity of a multilayer mirror obtained by varying only the two porosities in the measured mirror stack. Fig 2 shows the modelled increase and narrowing of emission of a photonic mode as the gain is increased within a structure.

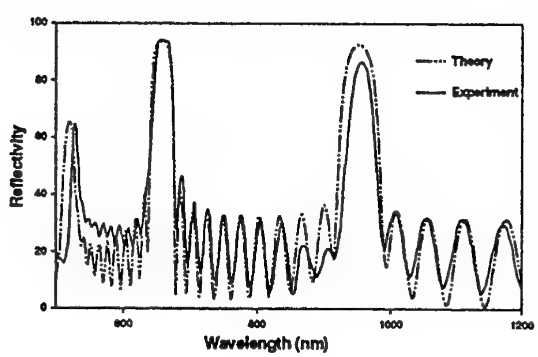

Fig. 1 Reflectivity of mirror structure

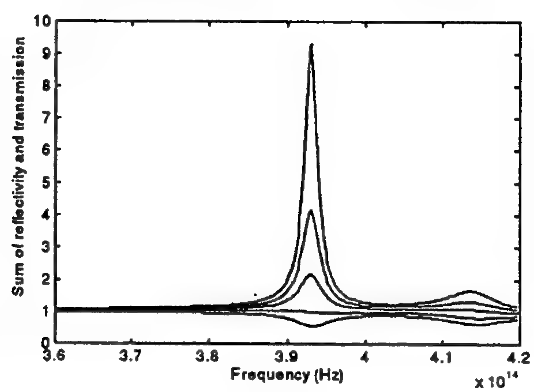

Fig. 2 Modelled increase of emission.

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NOVEL PHOTONIC CRYSTALS FOR THE MICROWAVE REGIME

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The subject of photonic band gaps (PBGs) is now ten years old [1,2]; the first experimental manifestation of the band structure for a three-dimensional (3D) photonic crystal was demonstrated at microwave frequencies [3]. Current fabrication attempts to produce photonic crystals are aimed principally at applications for optical wavelengths, associated with crystal periodicities around the micron scale. The fabrication of such crystals presents a severe technological challenge, just beyond the limits of current capabilities. The study of microwave-scale structures, however, remains a valuable exercise, for the development of practical and useful structures, such as filters and waveguides at microwave wavelengths, and for modelling structures designed for optical wavelengths. Although the viability of 3D microwave photonic crystals has been demonstrated, fabrication has been limited to only a small number of crystal structures [4,5]. It is desirable to have the ability to create crystals of arbitrary structure, and with arbitrarily designed defects.

In this talk we present a novel method of microwave photonic crystal fabrication which is flexible, fast, and simple. We have exploited the technology of Rapid Prototyping (RP), which provides the facility to create almost arbitrary 3D structures previously specified using computer aided design. To date we have constructed crystals by means of a Stereolithography apparatus, which builds up the object by UV laser addressing of a photo-curable polymer. Although the refractive index of the polymer is not high enough (in comparison with that of air) to produce a full photonic band gap material, it is possible to fill a crystal with a higher-index material to exceed the critical index ratio of 2:1. The method also offers the possibility of modelling in practice 3D crystals with features such as curved surfaces or variable periodicity that are at present too complex to analyse or model numerically.

We also describe a novel face-centred-cubic crystal structure, with diamond symmetry, specially suited to this form of build, which is highly economical in its computer file size. Using this structure we have constructed sheets of different crystal orientation, and measured the transmission and reflection properties of each. Finally, we shall describe the properties of such crystals with engineered planar and isolated defects.

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MULTIPLE-QUANTUM-WELL BINARY-PHASE MODULATORS: GENERAL DISCUSSION.

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Over the last thirty years, various types of two-dimensional (2-D) phase modulators have been proposed and demonstrated, which rely on a mechanical, magnetic, thermal or electrical form of modulating mechanisms [1]. Following John Neff's wish list [1], ideal 2-D SLMs arrays should possess the following characteristics: compatibility with Si-based electronics in drive voltage levels (around 3.3 V) and manufacturability, high frame rate (>100 MHz), low switching energies (femtojoules) per pixel, high resolution (10 μm pixel size) and large dynamic range if analogue operation is required (>20 dB), good uniformity of the device optical response across the array and large tolerance with respect to its structural or operational parameters. Unfortunately, some the modulation mechanisms proposed have response time, activation energy or spatial scale which do not comply with the above requirements. For example, it is unlikely that mechanical SLMS with tens of MHz frame-rate will ever be possible. The inherent low-throughput efficiency (less than 10%) and heat-dissipation of the "LIGHT MOD" array makes it expensive to manufacture and difficult to integrate with Si-based electronics. In the same way, the molecular orientation in liquid crystal displays has intrinsic speed limitation which results in array reconfiguration times of at least a few microseconds. The thermal modulating mechanism is known to be inherently slow and impractical for real-time applications. Recently, π-phase modulation in a vertical cavity asymmetric MQW Fabry-Perot modulator was experimentally reported by Trezza et al. [2]. The large absorption changes ($\Delta\alpha$) induce a change in the dominant role played by one of the cavity mirrors, achieving an exact phase change of π when the induced refractive index change (Δn) is zero. Moreover, the device, named phase-flip modulator, is designed so that no change in throughput is induced at the voltage swing. The elimination of the electro-refraction effects, the π-phase modulation at constant intensity throughput requires a careful design of the quantum well structure, the spacer material and the mirrors as well as the precise determination of the operating wavelength and voltage swing. The purpose of this article is to analyse which of structure, operational and physical parameters defined later on, are critical in achieving the best overall device performance, the optimum operating conditions and the largest degree of robustness, the tolerance, to the fluctuations in device characteristics. In that respect, we follow closely the tolerance methodology applied successfully to SEEDs [3] .

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SPONTANEOUS EMISSION CONTROL IN EDGE EMITTING QUANTUM WELL LASER DIODES

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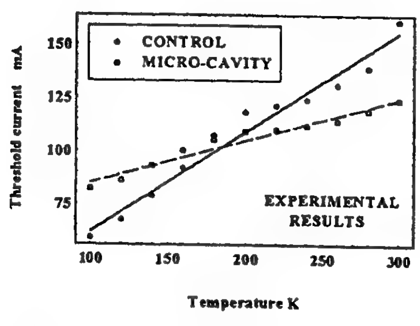
The reduction in threshold current in semiconductor lasers is limited by spontaneous radiative recombination. Only a small fraction (10^{-3} - 10^{-5}) of this is emitted in to the lasing mode and the remainder is an intrinsic loss. We have investigated the control of spontaneous emission by incorporating the QW emission layers within a planar optical micro-cavity. We have fabricated AlGaAs QW lasers, micro-cavity devices with epitaxial DBR mirrors cladding the QW region and control devices identical but for a mean alloy cladding replacing the DBR structures.

Experiments show that a micro-cavity device has a 25% reduction in threshold current compared to its control device.[1] The temperature dependence of the threshold current is shown below. As can be seen, the difference in threshold between the two devices reduces with decreasing temperature and the control device has a lower threshold below 150 K.

We have calculated the gain / current characteristic for both the micro-cavity and the control structure using Fermi's golden rule. The model includes both light hole and heavy hold transitions by considering the polarisation dependence of the optical mode density, electric field strength and dipole matrix element. The 3-D optical mode density and electric field strength calculations are solved numerically using a transfer matrix method in a planar geometry.

We show that the gain / current relation is not an intrinsic property of the QW material but is also dependent on the cavity structure. The temperature dependence of the two laser structures and comparisons of our theoretical model with experiment will be discussed.



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GUIDED MODES IN A PHOTONIC CRYSTAL FIBRE

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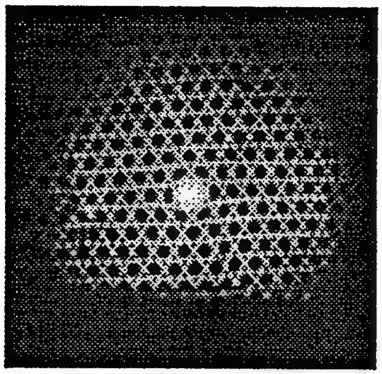

Figure 1 Optical micrograph of a photonic crystal fibre, of diameter 80μm.

Photonic crystal fibre (PCF) is a unique form of low-loss optical waveguide, which works by trapping light in a defect within a two-dimensional silica/air photonic crystal material (see figure 1).[1] The photonic crystal material is formed by a 2 dimensional array of small, closely-spaced (1-5μm) air holes which run down the length of the silica fibre. The defect is a region of pure silica embedded in the holey material. Although it guides by total internal reflection, as do conventional fibres, we have found that PCF has properties which are fundamentally different to those displayed by other fibres. These properties are determined by the design of the unit cell of the crystal cladding material – the shape, the pitch and the air-filling fraction – as well as by the size of the defect core. The photonic crystal is a new type of optical material, so there is considerable scope to fabricate fibre with novel properties. For example, we have demonstrated a fibre with a simple hexagonal array of air holes in the cladding which is single-moded over an extraordinary wavelength range extending from 337nm to beyond 1.55μm, a result which is supported by theoretical considerations.

By increasing the size of the air holes in the structure one increases the effective index difference between the silica core and the silica/air cladding, increasing the number of guided modes. Likewise, the use of more complex unit cell structures as illustrated here can result in more guided modes (figure 2). The talk will describe more fully the dependence of the number of guided modes on the design of the photonic crystal cladding.

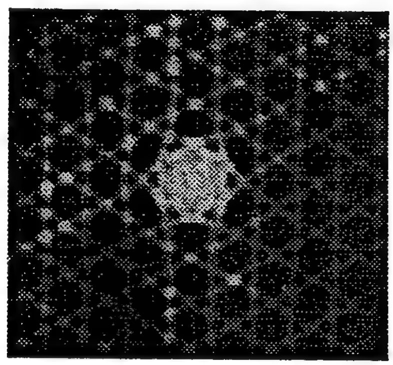

Figure 2 Higher-order mode in the core of a photonic crystal fibre. The core diameter is approximately 8μm.

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PHASE-MATCHED EXCITATION OF WHISPERING GALLERY MODES IN MICROSPHERES USING A FIBRE TAPER

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Whispering gallery modes in fused-silica microspheres (WGM) are high Q microcavity modes. They can provide a very high field per photon in the cavity at optical frequencies, making them of interest for many applications.[1] These require efficient excitation of the resonant mode, by coupling it to an external optical field. We have recently demonstrated that the most efficient excitation method is to couple them directly to the guided mode in a tapered single-mode optical fibre.

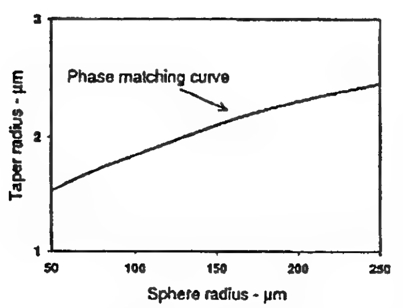

Figure 1 Phase matching curve for WGM excitation using a taper.

Our microspheres are formed by fusing the end of a fine silica fibre. Fibre tapers are made by heating and stretching a section of optical fibre to form a narrow waist. In this waist the guided mode has an evanescent tail extending out into free space, and its propagation constant is a function of the waist diameter. By adjusting the waist diameter one can phase match the guided mode to one of the resonances in the sphere. This is important because a mismatch will limit the maximum attainable coupling efficiency. Figure 1 shows the radius of fibre taper required to phase match to a WGM for different sphere sizes.

Experiments were done using a tuneable 1.5µm laser. The taper waist was placed in contact with the microsphere and the transmission through the fibre taper was monitored as the wavelength was scanned across a microsphere resonance, as shown in figure 2 for a sphere of radius 85µm. Over 72% of the light was coupled out of the fibre on resonance: off-resonance coupling was below detectable limits. Similarly, we have observed a coupling of over 90% using a somewhat larger sphere of radius 210µm. These figures represent a significant improvement over previously reported values for the coupling efficiency using other excitation methods.

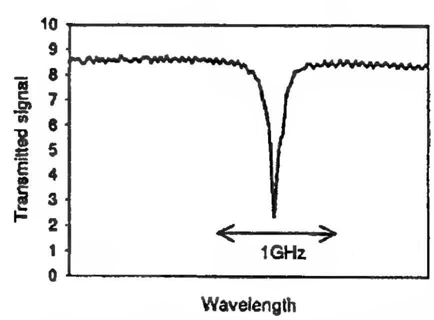

Figure 2 Transmission through the fibre taper as the wavelength is scanned.

(1) See e.g. *Optical Effects Associated With Small Particles*, P. W. Barber and R. K. Chang, Eds., (World Scientific, Singapore, 1988)

MACROSCOPIC QUANTIZATION IN QUANTUM OPTICS AND CAVITY QUANTUM ELECTRODYNAMICS: INTERATOMIC INTERACTIONS

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ABSTRACT

We extend previous work on macroscopic canonical quantization leading to a multipolar Hamiltonian appropriate for application to quantum optics and cavity QED situations involving classical optical devices. In particular, we show that the electric displacement is the negative of the conjugate momentum field and that the Coulomb and polarization energies are equal to the sum of intratomic Coulomb and polarization energies and interatomic contact energies. The quantum Hamiltonian is now in a form in which the theory is manifestly gauge invariant.

Spontaneous Decay in Metal/Vacuum Photonic Microstructures

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We consider spontaneous emission in photonic structures composed of materials with naturally occurring photonic band-gaps. These are principally two-component periodic systems in which one or both components have frequency-dependent dielectric functions. Metals have been highlighted as particularly interesting in this context. We have studied spontaneous emission in two basic structures (a) a multilayer system of metal layers separated by vacuum layers, and (b) hollow cylindrical metallic structures. Dipoles located within the hollow regions of the structure can only decay by emission into the available mode channels of the structure and would therefore have a modified decay time relative to free space, depending on the dipole frequency, orientation, structure dimensions and material parameters.

Results of the theory in (a) are presented for the decay rate as a function of the metal dimensions and for varying dipole frequency. For an aluminium/vacuum multilayer we show that the effect of the periodicity is to open up new bands and band gaps within the forbidden gap below the metallic plasma frequency and that these bands provide new spontaneous decay channels. The characteristics of the structure are shown to be controllable by varying the dimensions of the aluminium regions. This gives rise to decay response spanning the frequencies from the UV to the visible regions of the spectrum. We also show that in the limit of infinitesimally thin aluminium sheets the frequency response is concentrated in a single band located in the low frequency region and this is shown to be sensitive to the dimensions of the vacuum layers and the nature of the metallic sheets. Results of the theory in (b) are presented as spontaneous decay rate against the cylinder dimensions. The decay rate is shown to be considerably reduced in this case relative to free space because of the discreteness of the modes imposed by the confinement in two spatial directions. The effects of the periodicity in the cylinder array case are pointed out and discussed.

MODIFICATION OF SPONTANEOUS EMISSION BY DIELECTRIC MEDIA

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In their papers [1,2] of 1992, 1996, the authors have given a theory of the decay of excited atoms in absorbing dielectrics which repeats (without reference to much of it [3-6]) much previous work on this problem, and which manages to introduce all of the errors of conceptual understanding that have bedeviled the study of the so-called "internal fields" in dielectrics since the first really significant work of Lorenz and Lorentz [3] on this problem. The problem of the internal fields in dielectrics is addressed and solved, as a strictly many-body theoretical solution however, in the papers [3,4,5] of (1984)-(1990) made available to the authors of [1,2] in 1993: the modifications of the A-coefficients which *may be said* to occur in such dielectrics are definitively analysed there [6]. This is done in terms of a free-field tensor propagator or Greens function $\mathbf{F}(\mathbf{r},\omega)$ [3] carrying all-orders of interatomic scattering inside the dielectric; *or,* alternatively *but equivalently,* it is done in terms of a screened Greens function $\tilde{F}(\mathbf{r},\omega)$ [4,6]: $\tilde{F}(\mathbf{r},\omega)$ is also introduced in [2,7] and depends on the complex dispersive refractive index (called $m(\omega)$ in [3,6]) of the system. But, in contrast with [1,2], [3,4,5] *solve* for $m(\omega)$ consistently as a many-body problem.

Contact with the A-coefficient (and with [2]) is made via the self-correlation $\delta(\mathbf{r})$ and the radiation reaction $\int\delta(\mathbf{r})\ \tilde{F}(\mathbf{r},\omega)\ d\ (\mathrm{vol}) = \frac{2}{3}\, i\, m(\omega)\omega^3 c^{-3}\mathbf{U}$ ($\mathbf{U}$ is the unit tensor) thus gaining the factor $m(\omega)$ compared with the free-field description in $\mathbf{F}$ - the main burden of [1]. The additional longitudinal decay in [2] is a 'near field' effect [7] necessarily contained, and its divergences properly handled, in [3,4,5]. But the 'confirmation' in [7] of the modified A-coefficient $\Gamma_0 \rightarrow m'(\omega)|(m^2+2)/3|^2$ ($m'(\omega) = Re\ m(\omega)$) guessed at in [1,2] is not correct - because interatomic correlation is not all considered in [1,2,7]. In this Poster we give a considered estimate of the proper form of the A-coefficient in real dielectrics.

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3. Quantum Well Devices

SPATIAL SOLITON PIXELS IN SEMICONDUCTOR DEVICES

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Spatial solitons have been predicted [1] and observed (C.O.Weiss, private communication) in saturable absorbers. Here we investigate such spatial solitons in broad area semiconductor microresonator models in two basic configurations: a passive multiple quantum well (MQW) structure; and a vertical–cavity surface–emitting laser kept above transparency but some 5–10% below threshold (with population inversion the usual self–defocusing nonlinearity is converted into self–focusing, assisting soliton formation). We take account of carrier diffusion as well as diffraction in the modelling.

Our studies involve both dynamical simulations and direct radial integration to find the stationary soliton solutions [1]. The parametric domains where they exist, are of sizable extent and accessible to experimental realisations. Figure 1 shows typical examples. These results suggest that the realisation of an array of spatial soliton pixels using semiconductor materials is feasible despite diffusion and, sometimes, self–defocusing.

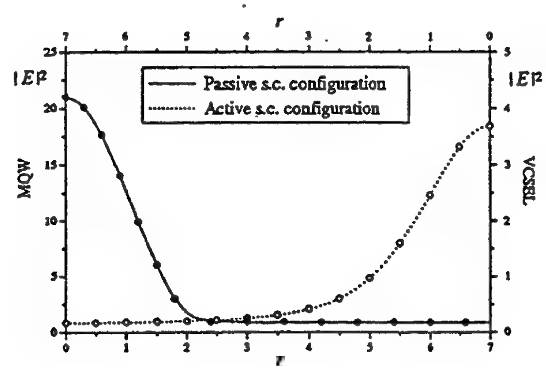

Figure 1: Radial profile of the spatial soliton for both the passive (left) and the active (right) s.c. device. Results obtained by numerical simulations (symbols • and o in figure) fit closely to the radial integration results (solid and dotted lines).

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ELECTRON SPIN RELAXATION IN InGaAs/InGaAsP MULTIPLE QUANTUM WELLS

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Spin relaxation of carriers in III-V semiconductor quantum wells is of interest not only in view of the fundamental physics involved, but also in its application for spin dependent optical devices. Previous studies have shown that the spin recovery time of electrons in GaAs quantum wells at room temperature is of the order of several tens of picoseconds[1]. Of more interest for optical communications applications are spin recovery processes at 1.55μm in InGaAs/InGaAsP multiple quantum wells. In this paper we report fast spin recovery times in this material system, which may be useful for all optical switching.

We have measured the spin recovery time of InGaAs/InGaAsP quantum wells using the spin dependent excitonic optical nonlinearity with the pump-probe technique. The sample consisted of 60 periods of 9.5nm wide InGaAs quantum wells separated by 7.5nm wide InGaAsP barriers, grown on an InP substrate. The electron heavy hole exciton peak was observed at 1510nm at room temperature. A KCL:$Tl^0(1)$ colour-centre laser was used as the source for the pump-probe experiment. The pulse duration was 150fs and the spectral width of the pulses was 20nm.

When excited by a circularly polarised pump pulse, resonant with the heavy hole exciton, 100% spin aligned carriers were created. After excitation, the carrier populations were probed by a pulse having either the same or opposite circular polarisation. The spin polarised electrons relax to an equilibrium of 50% spin up and 50% spin down.

A clear exponential decay of the transmission at the heavy hole exciton peak was observed for the same circular polarisation case and an exponential rise observed for opposite circular polarisation. The exponential decay time constant was measured to be 25ps. This value is significantly greater than the relaxation time of 5.2ps recently reported[2].

In conclusion, we have investigated the electron spin recovery dynamics in InGaAs/InGaAsP quantum wells using a time-resolved pump-probe method. The spin recovery time in an InGaAs/InGaAsP quantum well was found to be 25ps at room temperature.

This work was supported by the Engineering and Physical Science Research Council (EPSRC). We acknowledge C. Button for providing the sample.

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GAIN MECHANISMS IN ZnSe/(Zn,Cd)Se MULTIPLE QUANTUM WELLS

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Optical gain spectra of a ZnSe/(Zn,Cd)Se based multiple-quantum-well structures are presented, up to and beyond the excitation level where gain arises from both electron-heavy-hole and electron-light-hole recombination in an electron-hole plasma.

Primary data is from a structure grown by molecular beam epitaxy, and consisting of 50 quantum wells with a nominal Cd concentration of 16%, a well width of 40Å, and a barrier width of 80Å. Gain spectra were obtained by the variable stripe length (or *Shaklee*) method. The pump laser was an excimer pumped single longitudinal mode dye laser, giving pulses of 2ns duration (FWHM). Excitation was tuned to give pumping of the quantum wells without pumping the barriers or the cladding layers, and without significant direct excitation at the heavy and light-hole absorption features. This ensured that bleaching of the absorption at the pump frequency did not occur.

The results for the primary sample show the transition into net gain, where the gain overcomes losses in the sample due to defects and other scattering centres. At higher excitations, a second, higher (photon) energy, feature emerges in the gain spectrum. The separation of the two features is 28 meV, the same as the splitting between the heavy- and light-hole sub-bands. This leads us to conclude that the lower (photon) energy feature is associated with a heavy-hole gain process and the second, emergent, feature is associated with a light-hole process. Polarisation dependence of the emission spectrum is consistent with the above interpretation.

At the excitation level where light-hole gain first appears, the light-hole sub-band is just reaching inversion, inferring that the chemical potential for the holes is 28 meV (the separation of the heavy- and light-hole bands). Using this chemical potential along with knowledge of the band structure from an 8×8 **k.p** band structure calculation, allows us to calculate the carrier density (1×10^{19} cm^{-3}) and carrier lifetime (100ps), at that excitation level.

It is known that gain in such samples is excitonic at low temperatures and due to an electron-hole plasma at high temperatures. Results, from investigations now underway, over a range of temperatures and well widths which span this transition will be presented.

MULTIPLE QUANTUM WELL BINARY PHASE MODULATOR

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Over the last thirty years, a considerable amount of work has been carried out on the design and fabrication of two-dimensional (2-D) phase modulators, ranging from liquid crystal devices to deformable mirror displays [1]. The modulator presented here relies on the Quantum Confined Stark Effect-induced change in absorption within a Fabry-Perot (FP) cavity which switches the dominance of the role played by one of the two mirrors thereby achieving a π phase change [2]. The MQW device can potentially switch between phase states in a much shorter timescale (<1 ns) than can be achieved using liquid crystals (>10 μs). This fast spatial reconfiguration of a phase profile has several interesting applications ranging from beam steering devices (optically controlled radar, reconfigurable interconnections) to fast adaptive optics.

We report an MQW device that modulates the phase profile of a beam at a wavelength of 850 nm. The device consists of a Fabry-Perot cavity with a series of 55 $GaAs/Al_{0.3}Ga_{0.7}As$ MQWs incorporated into the spacer region to provide a variable absorption medium within the cavity. The front mirror consists of 15 pairs of $AlAs/Al_{0.3}Ga_{0.7}As$ and is p-doped to form the top contact pad. The back mirror is n-doped and is made of 24 pairs of $AlAs/Al_{0.3}Ga_{0.7}As$. An array of such devices has been fabricated in the form of 32 fingers, each of which can be individually addressed via one of 32 contact pads surrounding the fingers, figure 1. This allows a variety of phase patterns to be written to produce a binary phase grating. A phase-shifting interferometric microscope has also been developed to measure phase differences across the array.

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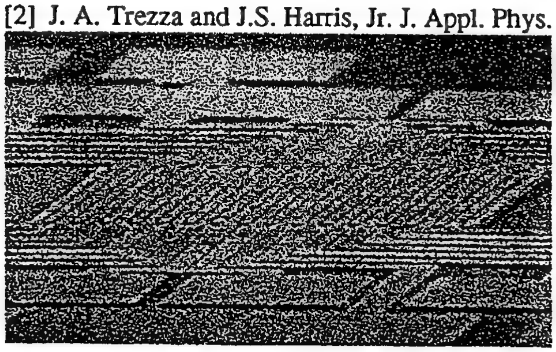

Figure 1. Photograph showing the 32 fingers in the centre of the array. Contact pads can be seen above and below the fingers.

QUANTIFYING INTERMIXING OF GaAs/AlGaAs QUANTUM CONFINED HETEROSTRUCTURES THROUGH KINETICS OF DEFECT DIFFUSION

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Intermixing of quantum confined heterostructures is an attractive alternative to regrowth and overgrowth techniques for realising photonic and optoelectronic integrated circuits. Although quantum well intermixing (QWI) was first reported in 1981,[1] no comprehensive mechanism of the process was presented until 1988.[2] To date the majority of research has been directed at experimental investigations of the processes. Despite the advances in the technology of QWI, a comprehensive qualitative model would permit further process optimisation. It would also assist in establishing intermixing technologies in more complex semiconductor systems such as InP-based quaternaries.

Compositional intermixing, and hence, Al and Ga interdiffusion, in GaAs/AlGaAs heterostructures is either carried out directly through diffusion of group III vacancies or is assisted by the formation of group III Frenckel defect pairs, through the diffusion of group III interstitials. The vacancy diffusion length, L_D, can be viewed as a result of a random walk which consists of a certain average number of lattice hops, determined by the hop rate, and hence by the diffusion coefficient of the vacancies. For an AlAs/GaAs heterostructure, on each occasion that a V_{III} crosses the plane of the quantum well, a Ga atom moves one lattice site out of the well into the barrier. Thus the number of times a group three vacancy crosses the QW/barrier interface should be directly proportional to the number of lattice hops needed to comprise the Ga complementary error function diffusion profile.[3]

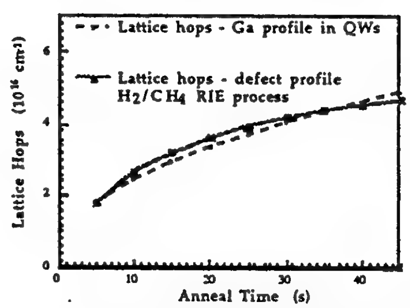

Fig. 1. Plot for the number of lattice hops (a) needed to obtain the measured amounts of intermixing, (b) predicted from the model for the given defect profile.

Calculations of the amounts of intermixing excepted in GaAs/AlGaAs quantum wells have been carried out for the process of impurity free vacancy disordering[4] as well as plasma induced defect layer disordering.[5] Results were found to agree with the values measured experimentally. As can be seen in Fig. 1, for a vacancy surface recombination velocity of 5.9 nm s^{-1} the number of lattice hops calculated using the model agrees within 10% from the measured values.

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EXPERIMENTAL INVESTIGATIONS OF MQW INGAAS ON CMOS SMART PIXELS FOR OPTICALLY CONNECTED COMPUTERS

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Extensive use of optoelectronic interconnections is likely to be needed to meet the bandwidth requirements of tomorrow's information processing systems. Recent work has suggested that smart pixel arrays in conjunction with free-space optics are a very promising solution. III-V Multiple Quantum Well (MQW) modulators and detectors integrated with silicon circuitry to produce smart pixel arrays have been developed by a number of groups. This combination exploits the versatility of silicon circuitry together with the optoelectronic properties of III-V devices, and has the capability to achieve chip-to-chip interconnect data transfer of greater than 1 Tbit/s.

We have developed hybrid smart pixel devices for a number of optical processing systems. One particular device, designed for a bitonic sorter system, has 16 smart pixels, each with optical input/output, electrical input/output, and a 24-bit shift register memory. This allows the transfer of data from the serial electronic domain and into a parallel optical domain, and vice-versa. The device is based on InGaAs detectors and modulators, flip-chip bonded onto custom-designed CMOS chips. Each pixel has two PIN diodes as receivers, a transimpedance amplifier, a 24-bit shift register, with electrical control, and two transmitter PIN diode modulators. The system was designed for dual-rail differential optical signals to improve the signal-to-noise ratio, therefore two diodes are required for modulation and detection. The device was designed to operate at 1064 nm, where the GaAs substrate is transparent, and high power Nd:YAG lasers are available.

The InGaAs chips have been successfully flip-chip bonded onto the CMOS, and testing in the optical system environment is at a preliminary stage. Electronic data in the CMOS circuitry can be clocked over 100 MHz. Data has been successfully transferred from the electronic shift registers to the optical domain at a clock rate of 120 MHz, and optical data can be transferred into the electronic domain at a similar rate. With temperature control to optimise the operating conditions, a contrast ratio of up to 2.5 was measured around the design wavelength. This is safely above the minimum contrast needed for system operation.

This paper will present progress of this work, including the results of the transfer of optical data between the smart pixels, and overall system performance. An evaluation of system performance will then be given in terms of current and future requirements. The characterisation of practical optoelectronic devices of this type, in a typical operating environment, will allow the potential of this technology for future computing applications to be realistically assessed.

4. Semiconductor Lasers

Controlling chaotic dynamics in external cavity laser diodes using impulsive delayed feedback.

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Abstract

Interest in controlling semiconductor laser dynamics [1-3] has been stimulated ,in particular , by the possibilities for achieving secure communication systems which exploit the properties of chaotic dynamical systems.Another practical context where chaos control techniques may have an important role to play is in engineering immunity to coherence collapse caused by unintentional optical feedback which may arise in the hybrid integration and packaging of commercial laser diodes.

In this paper the possibility of chaos control in a model of an external cavity laser diode with optimized impulsive delayed feedback is demonstrated. An examination is made of the application of such feedback via different laser parameters such as electric pumping, a laser field phase increment in the external resonator and cavity losses in the presence of intrinsic noise [4] . Account is taken of practical constraints arising from technical delay in application of the control signal The role of the phase, width and shaping of feedback pulses for optimizing the control process is elucidated.

Acknowledgements

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STRONG OPTICAL FEEDBACK EFFECTS ON THE DYNAMICS OF MULTI-LONGITUDINAL MODE LASER DIODES

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Abstract

The dynamics of semiconductor lasers subject to optical feedback is of great practical importance due to its significance for the performance of packaged laser diodes and also for laser diodes in hybrid optical integration schemes.Despite being the subject of considerable work over many years , understanding of the behaviour of laser diodes in such configurations is far from complete.In practical laser diodes effort is,in particular , required to elucidate the spectral features of laser diodes when subject to optical feedback . At a more fundamental level , a full classification of the dynamics of such devices represents a major challenge - not least due to the absence of a mathematical framework for a rigourous description of the associated bifurcation phenomena which can arise.

The present paper seeks to address practical issues arising in multimode laser diodes subject to strong optical feedback. A multimode iterative analysis is applied to the study of dynamical effects arising in both short and long external cavities [1]. The model is applied to a specific topical phenomenon - the observation of low-frequency fluctuations (LFF) far above threshold in external cavity lasers [2].It is shown that the present analysis captures the underlying fast dynamics associated with these LFF.It is known that in near-threshold LFF the laser suffers power drop-outs .In contrast , well above threshold 'jump-up ' phenomonena are found in the analysis - in agreement with experimental observations.

Acknowledgements

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PUMP/PROBE DEPLETION EFFECTS ON MULTI-WAVE MIXING IN SEMICONDUCTOR LASERS

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Abstract

Multiwave mixing in semiconductor lasers is of interest for frequency translation and spectral inversion in long-haul optical communications systems and also for the generation of phase conjugate signals which may be used in turn to influence the noise and linewidth properties of other semiconductor lasers. In earlier work [1] attention has been given to the opportunities for achieving enhanced nearly degenerate multiwave mixing through careful cavity design of Fabry-Perot laser structures .In particular the use of asymmetric two-section laser diodes was shown to offer the prospect of broadband laser diode phase conjugate reflection [2] and enhanced tuning [3] . Recently attention has been given also to highly degenerate four wave mixing in DFB lasers [4].

In the present paper attention is given to limitations on achievable mixing efficiency due to effects of pump and probe depletion and also due to carrier diffusion effects. The former is of significance when strong input signals are used in the mixing process whilst the latter arises in asymmetric laser structures.The inclusion of these effects is thus important for practical applications of enhanced multiwave mixing and phase conjugation.

Acknowledgements

J.M.Tang is supported by the Wynn Humphrey Davies Studentship of the University of Wales,Bangor and by SEECS,University of Wales,Bangor. This work also is partly supported by EPSRC under grant GR/L03262.

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Modelling Pulse Propagation in Semiconductor Optical Amplifiers using Wavelets

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Optical pulse propagation in semiconductor optical amplifiers is described by the nonlinear Schrödinger equation which is often solved using the split-step Fourier method [1]. Here an alternative approach is presented in the form of a split-step wavelet technique. Wavelets yield a time-scale representation of optical signals which is closely linked to conventional time-frequency representations.

The transform at the heart of the present algorithm splits a signal into 'wavelets' rather than frequencies that stretch over the whole width of the signal. Some wavelets in a basis set are broad, with only a few required to cover the whole pulse width and correspond to a large scale approximation of the signal. Other wavelets are narrow and only cover a small fraction of the same time interval, and correspond to local, high-frequency details in the signal. A strength of this representation is that only a subset of the possible wavelets are required to adequately describe an optical signal. The wide wavelets give a large scale approximation, which is refined *only where needed* by smaller scale, narrow wavelets. This means that the wavelet tranform of an optical signal is a sparse representation.

When a signal is represented by N samples the FFT method requires $O(N \log N)$ operations. In contrast the present method requires $O(N)$ operations [2] with an associated speed advantage.

The wavelet approach has been previously applied to studies of signal propagation in optical fibres [3]. In the present paper we use a biorthogonal wavelet basis set which diagonalises the propagation operator matrix [4] to study subpicosecond pulse propagation in semiconductor optical amplifiers [5].

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NORMAL INCIDENCE OPERATION IN N-TYPE UNIPOLAR OPTOELECTRONIC DEVICES: TE INTERSUBBAND MATRIX ELEMENTS

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Optoelectronic device operation based on quantum well intersubband transitions offers a number of potential advantages over devices utilising interband transitions. Of particular significance is the ability to access transition energies, in technologically well developed materials systems, much lower than those readily accessible by interband transitions, allowing operation at wavelengths not currently well served by interband devices. Intersubband transitions allow the possibility of highly temperature stable device operation at long wavelengths, due to the relative insensitivity of intersubband transition energies to temperature variation, when compared against interband transition energies, and due to the virtual elimination of Auger losses. Unipolar device operation in other than the more conventional bipolar PIN-diode configuration could also have benefits for device figures of merit such as applied operating voltage.

Both n-type and p-type systems have the potential for use in optical modulators, photodetectors, non linear devices and unipolar lasers. However, n-type intersubband transitions can benefit from such features as nearly parabolic subband structure not easily obtainable in p-type quantum wells. In addition to the potential advantages of unipolar operation, normal incidence operation will be of value for quantum well intersubband device applications, for instance allowing applications based on planar arrays of devices. However, although TM operation is readily achievable in both n-type and p-type intersubband devices, TE intersubband operation is known to be strongly disallowed in typical n-type, direct gap quantum wells. Use of such TE intersubband transitions allowing the possibility of surface normal operation combined with the advantages of n-type, direct gap systems, means that it is of value to explore the extent to which (strictly non zero) TE intersubband transition strengths can be enhanced in appropriately engineered n-type quantum wells by use of strain, choice of material system and quantum well shape.

This paper examines the potential for such quantum well engineering, in particular looking at the implications for TE matrix elements of the sophistication of the model used to describe the quantum well subbands. The results of 1-band, 4-band and 7-band **k.p** effective mass theory models (2-band, 8-band and 14-band with spin) are compared and the possibility of exploiting both non square wells, and interband coupling described by bulk momentum matrix elements P_0, P_1 and Q, is discussed. The practicalities of basing unipolar device design on n-type material systems allowing such enhancement of TE intersubband transition strengths are also indicated and the possibility of surface normal emission in VCSELs, based on unipolar electron intersubband lasing, is given some consideration.

Operation of a multiple colliding pulse modelocked semiconductor laser at 1.55μm

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Modelocked semiconductor lasers are important sources of ultra short high repetition rate optical pulses for future lightwave telecommunications systems. Schemes for generating pulses at up to terahertz frequencies from diode lasers rely on modelocking at harmonics of the fundamental cavity repetition rate[1]. A significant technique is that of multiple colliding pulse modelocking (MCPM) in which 2, 3 or 4 pulses can be formed simultaneously in a laser diode cavity, harmonically multiplying the repetition rate of the laser, while maintaining the beneficial pulse shortening and stabilisation effects arising from colliding pulse modelocking[2]. In this paper we present the first demonstration of MCPM action from a laser diode operating at the fibre-optic low loss wavelength window around 1.55μm.

The laser (shown in figure(1)) consists of a standard ridge waveguide structure, but with the p-side contact split into several electrically isolated sections which form a gain section and three saturable absorbers. A novel wet etching method is used to produce the waveguide which provides the laser with a completely self-aligned current injection window. The active region of the InP/InGaAs/InGaAsP laser material used to fabricate the MCPM lasers contained two 13nm strained $In_{0.32}Ga_{0.68}As$ quantum wells (1.5% tensile) with 10nm InGaAsP barriers.

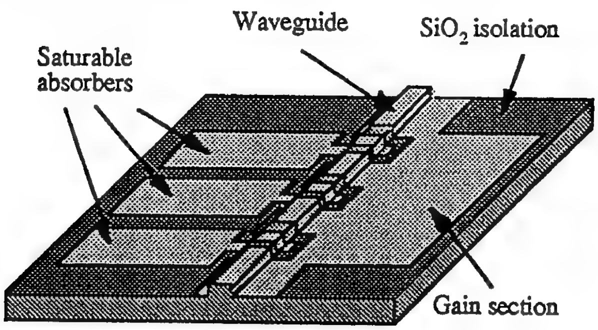
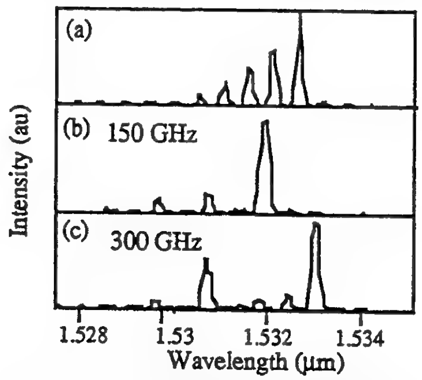


Figure (1): Schematic diagram of MCPM laser



Figure(2): Spectra for (a) non-modelocked (b) 2-pulse MCPM, (c) 4-pulse MCPM.

MCPM operation of a 600μm long device is illustrated in figure(2) which shows the laser spectra when the device is fully forward biased (2a), the central absorber only is reverse biased (2b), and all three absorbers are reverse biased (2c). Note the doubling and quadrupling of the wavelength mode spacing which indicates 2-pulse and 4-pulse MCPM operation at 150GHz and 300GHz respectively.

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Effect of inhomogeneity on quantum well far-infrared lasers

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Far-infrared (FIR) lasers working in the submillimeter range have wide uses in radio astronomy, communications and spectroscopy. In recent years, increasing research has focused on the design of FIR lasers using intersubband radiation in quantum wells (QW), e.g. [1]. Primitive experimental results [2,3] have shown the possibility of developing the structures into FIR lasers. This work discusses the effect of inhomogeneity on the QW FIR lasers.

As is well known, for a typical cavity length of $L \sim 1$mm of a GaAs/AlGaAs QW laser, the energy separations of resonant modes are $\Delta E = hc/2n_r L = 4.1 \times 10^{-12} \times 3 \times 10^{10}/(2 \times 3.72 \times 0.1) = 0.17$meV. We estimate the Lorentzian broadening to the gain width at $6.3 \sim 2.6$meV for the resonant wavelength 60μm and dephasing time $T_2 = 0.21 \sim 0.5$ps [4]. This number is much greater than the cavity energy separation. Therefore QW FIR lasers will not operate on a single longitudinal mode.

Inhomogeneity caused by the variations of QW width and composition can result in the subband drifting. For a stepped QW structure [5] with composition $x = 0.45$ at the barrier, $x = 0.22$ at the stepped well and the deeper well width $l_w = 7.6$nm, a one atom layer (0.286nm) increase in the well will cause a transition energy decrease of 3.4meV between the laser subbands; while 1% change in the composition will result in the intersubband energy fluctuating by 1.3meV. These two values are similar to or greater than the half gain width. So the QWs with these fluctuations can hardly contribute to the gain. Though these two kinds of inhomogeneity are independent and may cancel (as well as add) each other somewhat, inhomogeneity will still be a critical issue in manufacture of the FIR QW lasers. Fortunately, this can be compensated by increasing the number of QWs and relying on fluctuations to ensure that a significant number contribute to the gain.

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OPTICAL FEEDBACK SUSTAINED SELF-PULSATIONS IN SEMICONDUCTOR LASERS

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Self-pulsating semiconductor laser diodes are being used in many optical applications. A clear understanding of their working is therefore necessary to optimize their performances through a proper project.
The appearance of self-sustained pulsations has always been related to the presence, in the semiconductor material, of saturable absorbing centers. It is often assumed that these centers are separated from the active region and have their own dynamics which affects the one of the active zone.
We will discuss the case in which the saturable absorption mechanism is at work distributively in the whole active region. This choice makes us free from some troubling features of the two-section lasers with saturable absorption, i.e. the presence of different competiting cavities because of the existence of different sections.
We have modelled such a device with a couple of rate equations showing the presence of self-sustained pulsations. The non-linearity in the material is taken into account by a proper term related to photon density. The model presents a Hopf-bifurcation caused by the non-linearity. Its clear knowledge is essential for the control of both the laser output and dynamics.
Finally we investigated the effects of optical feedback taking into account the nonlinear dependence of the interband carrier lifetime on optical field intensity [1]. The links between feedback actions and saturable absorption has been already discussed [2] and we have obtained results that confirm the controlling ability of feedback both on amplitude and period of the pulsations. Actually, feedback can be responsible for the generation or quenching of the pulses.

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Techniques for minimising IVA loss in InGaSb/InAlSb/InSb quantum well lasers

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Uncooled Mid-IR sources are sought for a wide range of applications including gas sensing, environmental monitoring and free space communication. Bulk lasers with InSb active regions have been demonstrated with operating temperatures up to 100K. However the effects of Auger recombination and intervalence band absorption have been shown to make higher temperature operation of such devices unlikely. Consequently attention has been switched to the development of strained quantum well active region lasers where reduction in Auger recombination and intervalence band absorption are expected to allow increases in operating temperature to be realised. The structures being developed are grown on InGaSb substrates with InAlSb cladding layers, InAlGaSb barrier layers and InSb active regions. A major challenge in this work remains minimising the high IVA loss associated with the p-doped layers above the quantum well required for hole injection into the active region . This paper examines techniques for reducing this loss by investigating the variation of IVA with substrate orientation, and describes device structures which aim to minimise the confinement factor of the p-doped layers whilst maintaining good confinement of the lasing mode to the quantum well.

SELF-CONSISTENT ANALYSIS OF THE DIRECT CURRENT MODULATION RESPONSE OF UNIPOLAR SEMICONDUCTOR LASERS

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Intersubband semiconductor lasers have attracted considerable attention following the development by Faist , Capasso et al of Mid-Infra-Red (MIR) of the so-called Quantum Cascade lasers [1].That work gave the first practical demonstration of a long-standing proposal for the utilisation of intersubband transitions to obtain lasing action in semiconductor superlattices [2]. Quite considerable progress has subsequently been made by in improving the operating characteristics of those devices and it thus becomes relevant to assess the expectations of operating characteristics of intersubband laser devices including their anticipated current modulation capabilities .

In earlier work , use was made of the rate equation model described in [3,4] to derive expressions for the modulation response of intersubband lasers. It was observed [5] that since electron lifetimes in intersubband lasers are typically of the same order as the photon lifetime there is a fine balance between the contributions of the resonance frequency and damping factor in the determination of the maximum modulation frequency in these devices .That work,in particular, predicted the existence of an optimum optical output power to achieve the maximum modulation frequency is demonstrated [5] .

In that initial analysis representative values for carrier lifetimes and interwell tunnelling times were utilised.In the present contribution a self-consistent analysis of the modulation response is performed through a direct calculation of the relevant carrier and tunneling lifetimes for a prototype triple quantum -well structure suitable for incorporation in intersubband lasers.Opportunities for accessing predicted THz modulation capabilities in such devices are examined.

Acknowledgements

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QUANTUM NOISE IN SEMICONDUCTOR MICROLASERS

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SUMMARY

Microcavity semiconductor lasers have been shown to be promising devices owing to their characteristics such as very low threshold current, good optical beams, efficient fiber coupling, array capabilities, high speed, reduced intensity noise, etc. The peculiar characteristics of quantum noise in semiconductor laser with quiet pumping have been pointed out several years ago [1, 2]; neththertheless several aspects are not yet completely understood [3, 4]. In this paper a complete and self consistent model for the evaluation of intensity noise in a single mode semiconductor microcavity laser is presented; it includes the computation of spontaneous emission factor β and its dependence on the carrier density and device geometry (post structure) and the coupling of the laser equations with the electrical driving circuit. The last point introduces both the noise of the driving circuit and a correction factor, depending on the power supply internal resistance, which influences the noise spectra. These effects have been already pointed out, but they are usually neglected; however the influence of the driving circuit resistance can be relevant in particular for devices operating at room temperature which cannot work far above threshold.

After a general discussion of the noise problems, some simple asymptotic analytical espressions for the intensity noise will be given. Examples of numerical evaluations will refer to a post structure and the different contribution will be compared.

Work performed under ESPRIT-LTR Project ACQUIRE.

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5. Solitons and Patterns

NONPARAXIAL SOLITONS

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For paraxial light beams in Kerr waveguides, it is well known that a balance between nonlinearity and diffraction arises in the form of robust spatial solitons. Over the last two decades, a great deal of research effort has been invested in evaluating the potential that optical solitons have for exploitation as information "bits" in optical storage and processing systems. For compactness, and to maximise the information bandwidth of such systems, there is a general trend towards smaller "bits" and smaller devices. However, to realistically compete with existing information systems, this progressive miniaturisation entails the consideration of light beams which are increasing nonparaxial. The propagating electric field envelope, u, may then be described by the following nonparaxial nonlinear Schrödinger equation (NNLS)

$$\kappa\frac{\partial^2 u}{\partial z^2} + i\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial x^2} + |u|^2 u = 0$$

where z and x are the normalised longitudinal and transverse coordinates, respectively, and κ parametrises nonparaxiality.

We shall show that the NNLS possesses an exact bright soliton solution which is a three-parameter generalisation of the two-parameter fundamental bright soliton solution of the paraxial NLS ($\kappa = 0$). This balance point, between full 3D diffraction and Kerr nonlinearity, may define the optical information unit of minimum possible size. We will discuss the physical interpretation of the new nonparaxial soliton solution. In particular, an implicit inconsistency of the paraxial theory of off-axis propagation is uncovered. The results from a series of numerical simulations of the NNLS will be presented; dealing with a range of initial value problems and the predictions of the analytic work. To accompany this data, results from the solution of the direct scattering equations, analysing the asymptotic soliton constituents, will also be displayed.

Our numerical investigations have centred around studies of the formation, propagation and interaction of nonparaxial solitons. We have also considered the launching of high order paraxial solitons which undergo extreme narrowing – leading to a violation of the slowly varying envelope approximation and resulting in fission of the propagating beam into constituent nonparaxial solitons. For many materials, a leading higher order effect will be that of nonlinear loss (two-photon absorption) and this, itself, can lead to fission of the beam. Within the framework of the above, we shall also present an evaluation of the relative importance of nonlinear loss and nonparaxiality.

Doughnut solitons in quadratic nonlinear media and their fragmentation

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In recent work [1] on second-harmonic generation it was reported that frequency doubling with pump in the form of Laguerre-Gaussian beams with azimuthal mode index l generates a second harmonic with the doubled azimuthal mode indices $2l$. This is interpreted as due to the conservation of orbital angular momentum, which is l per photon for the fundamental, and thus must be $2l$ per photon for the harmonic. Also in quadratic media, spatial solitary waves (SWs) have been intensively studied by many authors both theoretically and experimentally. These facts prompt the question of whether SWs with finite angular momentum exist, and if so whether they are stable.

Here we report for the first time to our knowledge that families of mutually trapped SWs in a quadratic medium, with azimuthal phase modulation indices l and $2l$ for 1st and 2nd harmonic respectively, exist over a wide range of field energy and phase-mismatch. Their intensities have doughnut profiles with one or more rings around a central hole.

These doughnuts are generally unstable on propagation, breaking up into fundamental SWs. This break-up is a fascinating phenomenon, because it is as if a spinning flywheel disintegrates, tangentially throwing off solitons which fly out with constant velocity like Newtonian particles. We calculate this velocity from conservation of energy and angular momentum and show that the speed of an individual soliton does not depend on its energy and defines through the ratio of azimuthal indices to doughnut radius. These results are a very vivid demonstration of the particle-like properties of solitons, and of the significance of angular momentum in nonlinear optics. To predict the number of solitons N_s arising after doughnut break-up we performed doughnut stability analysis and found that N_s can be estimated as $2|l|$. It agrees well with numerical simulation in most cases.

Several recent experiments on spatial solitons, see e.g. [2], echo aspects of our observations, and thus provide an experimental background for the phenomena we study.

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THEORY OF MIXED-MODE SPATIAL SOLITONS IN ANISOTROPIC CUBIC MEDIA

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For media of cubic symmetry 432, m3m or $\bar{4}3m$ (e.g. zinc-blende semiconductors) a total of four coefficients are required to characterise the optical Kerr effect (ultrafast nonlinear refraction), which reduce to three coefficients for single wavelength operation.[1] Spectral broadening measurements in AlGaAs waveguides at a wavelength just beneath the half-bandgap indicate that there is a substantial nonlinear refraction anisotropy coefficient.[2] The slowly-varying envelope approximation provides coupled differential equations for the propagation of two orthogonal polarisation components, including the effects of birefringence. In the anisotropic cubic case there are a total of six orientationally dependent nonlinear refraction terms: self-phase-modulation, cross-phase-modulation, four-wave-mixing and three additional terms which only occur in the anisotropic case.[3]

Solving this case for the propagation of two coupled plane-waves leads in general to periodic solutions. A convenient method for determining these solutions is to consider the Hamiltonian for the problem; since the system is lossless the Hamiltonian and total power are conserved. The evolution of the polarisation state can therefore be displayed as contours of constant Hamiltonian on a Poincare sphere. There are stationary solutions (eigenpolarisations) which can be stable (centre) or unstable (saddle-point). It is found that as the ratio of nonlinearity to birefringence increases, that the initially stable TE and TM eigenpolarisations bifurcate. The fast mode bifurcates into two elliptically-polarised eigenpolarisations (as in the case of silica fibres[4]) and additionally the slow mode bifurcates into two linearly-polarised eigenpolarisations. For a conventionally orientated semiconductor waveguide and zero birefringence these stable eigenpolarisations are parallel to the [111] directions

Coupled nonlinear Schrödinger equations are obtained by including diffraction, which are the basis of describing mixed-mode spatial solitons. The evolution of these can also be plotted on a Poincare sphere by use of integrated Stokes parameters. The polarisation evolution in the soliton case is found to broadly follow the periodic plane-wave solution but the shedding of radiation results in a slow decay towards a stable eigenpolarisation.

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SPATIO-TEMPORAL OSCILLATIONS IN NANOSECOND OPTICAL PARAMETRIC OSCILLATORS

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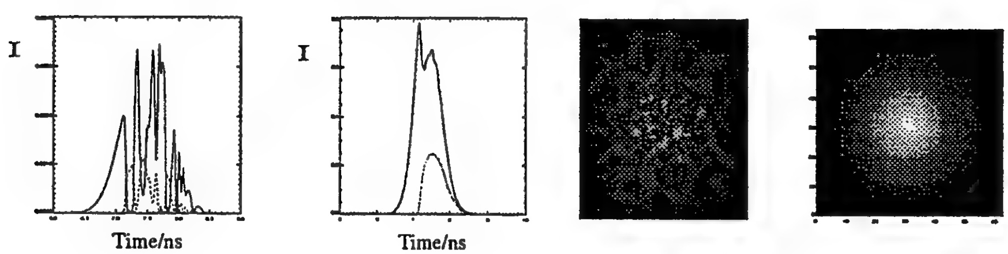
We present a mean field model for a non-degenerate, singly resonant optical parametric oscillator (OPO), appropriate for nanosecond pulsed operation. The basis of the model is an equation for the resonated signal field which includes the contribution of the pump and idler and was derived by generalising a method used by Longhi [1]. Our model currently takes account of diffraction and phase mis-matching. We numerically integrate the signal equation and reconstruct the pump and idler fields from the signal dynamics. The numerical integration of our model is by far faster than the simulation of the full set of OPO equations.

Here, we show evidence of local oscillations between the pump and idler (see first panel of the figure) which are smoothed when spatial averaging over the spot size is considered (see second panel). Such oscillations have not, to our knowledge, been observed experimentally since spatial averages are generally performed in experimental realisations. The local character of the oscillations is due to the spatial break-up of the signal field (see third panel) which does not follow the input gaussian profile (see fourth panel).

The influence of diffraction on the output fluence as well as the OPO beam quality will also been discussed.



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EFFECT OF SQUEEZING ON QUANTUM IMAGES

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We study spatio-temporal fluctuations in the degenerate optical parametric oscillator using the Langevin model of Gatti *et al.* The spatial structure of the output is calculated for pump values just below the threshold for the formation of patterns with a critical wavevector. We consider the effects of a squeezed input signal on the output correlations which can be measured in both the near and far-field.

The fluctuations in the output depend critically on both the amplitude and the phase of the squeezed input. The squeezed output can be greatly enhanced for some ranges of input squeezing (Fig. 1), whereas for others it becomes impossible to obtain any squeezing at all. Alteration of the input phase can change the transverse wavevector for maximum output squeezing. The transverse wavevector can be made smaller or (preferably) larger than the critical wavevector, thus making detection of the squeezing easier.

In the near field, for vacuum input the onset of pattern formation is anticipated in the spatial correlation function just below threshold. If a squeezed input is used then modulation in the correlation function is greatly enhanced, so this anticipatory behaviour will be easier to observe.

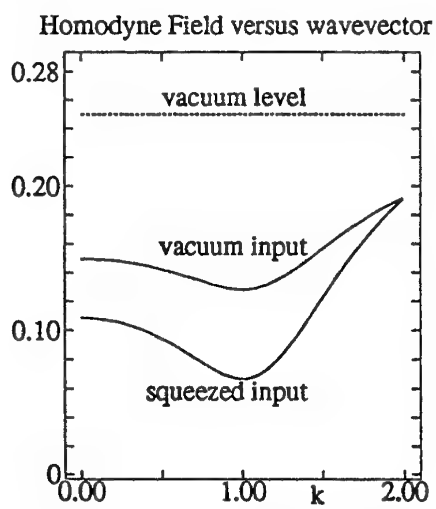

Figure 1: ***Homodyne variance against wavevector. The upper curve is the output for vacuum input and the lower curve is the output for slightly squeezed input***

Reference: A. Gatti, H. Wiedemann, I. Marzoli, L. Lugiato, G.-L. Oppo and S. M. Barnett, to appear in Phys. Rev. A (1997).

DOUBLE SQUEEZE: COMPRESSION IN BOTH SPACE AND TIME IN A KERR LENS MODE-LOCKED LASER MODEL

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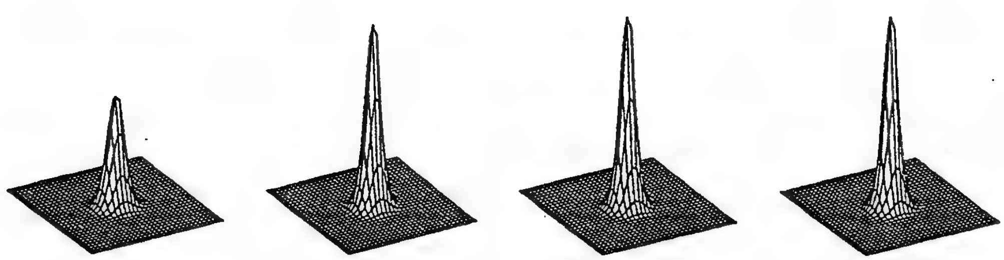
We discuss results from spatio-temporal simulations of KLM pulse evolution in an actively mode-locked laser. As shown in the time sequence below, a Kerr lens can substantially decrease the pulse length and beam width of an actively mode-locked laser and generate stable pulses, soliton-like in both space and time. Our analysis is based on our recently derived spatio-temporal master equation [1], which is applicable to any nonlinear cavity with linear spatial properties describable by an ABCD matrix, and one nonlinear interaction per roundtrip:

$$\begin{aligned} \frac{\partial E}{\partial T} &= \frac{i\psi}{2T_R \sin\psi}\left(\frac{B}{k}\frac{\partial^2 E}{\partial x^2} + i(A-D)\left(x\frac{\partial E}{\partial x} + \frac{E}{2}\right) + kCx^2E\right) \\ &+ i\beta\frac{\partial^2 E}{\partial t^2} + \alpha t^2 E + gE + i\kappa|E|^2E\,, \end{aligned} \tag{1}$$

where $\cos\psi = S \equiv (A+D)/2$ and T_R is the round-trip time, based on the group velocity. The constant parameters α, β may both be complex, and so may describe group velocity dispersion (GVD), gain bandwidth, and amplitude/phase modulation. g describes a uniform, linear, unsaturated gain or loss.
Numerical simulations in one dimension (x) show excellent agreement with the conventional Huygens integral method.



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6. Waveguide Structures

PROPAGATION OF FREQUENCY-DOUBLED LAGUERRE-GAUSSIAN BEAMS AND ROLE OF THE ORBITAL ANGULAR MOMENTUM

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Frequency-doubled Laguerre-Gaussian (LG) modes with a radial mode index $p = 0$ are themselves LG modes with twice the value of the azimuthal mode index[1]. This indicates that the orbital angular momentum per photon is doubled within the process of second harmonic generation[2].

We have frequency-doubled LG modes with $p \neq 0$ and show that the second harmonics form a new class of beam. We observe experimentally that the intensity distribution in the plane of the waist is reproduced in the far field, but is different in all intermediate planes (fig. 1). These results are consistent with our theoretical predictions.

Figure 1: Intensity cross-sections through a frequency-doubled Laguerre-Gaussian beam in different planes along its propagation axis

Despite these propagation characteristics, we conclude by measuring the azimuthal phase structure (fig. 2) that the orbital angular momentum per photon in the second harmonic beam remains well-defined and is twice that in the fundamental beam.

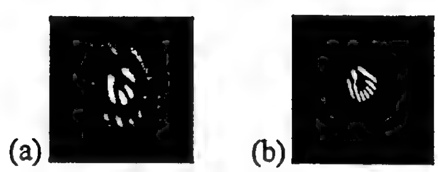

Figure 2: Phase structure of a LG mode with mode indices $l = 2$ and $p = 1$ (a) and of its second harmonic (b)

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THE TRANSFER OF ORBITAL ANGULAR MOMENTUM TO A LIGHT BEAM USING A STRESSED FIBRE OPTIC WAVEGUIDE.

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In recent years, the production of Laguerre-Gaussian laser modes has attracted considerable interest. This interest arose largely from the prediction that these modes, with an azimuthal phase term of $e^{i\ell\phi}$, have a well defined orbital angular momentum equal to $\ell\hbar$ per photon.

In this paper we present a new beam converter based on a short length of near single-mode, stressed, fibre-optic waveguide to convert a high order Hermite-Gaussian mode from a laser into a circularly symmetric beam with a well defined azimuthal phase dependence and corresponding orbital angular momentum.

To confirm the nature of the azimuthal phase structure, the output beam from the fibre optic is interfered with the expanded Hermite-Gaussian mode directly from the laser. Under low stress, the output beam resembles the input beam (figure 2a) and the circular fringes within the interferogram demonstrate that there is no azimuthal phase dependence. Under high stress, the output from the fibre is an annular beam (figure 2b) and the single spiral fringe within the interferogram shows the $e^{i\phi}$ phase dependence (figure 2c).

The lack of astigmatism makes this method of beam generation particularly attractive for use within an optical spanners configuration.

a b c

Figure 1. The output beam from the fibre: a) under low stress, b) under higher stress and c) under high stress interfered with a plane wave

TRANSFER OF ORBITAL ANGULAR MOMENTUM TO MICROSCOPIC PARTICLES SUSPENDED IN AN ION TRAP

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In 1992 it was predicted that Laguerre-Gaussian light beams possess a well-defined orbital angular momentum[1]. This angular momentum is directly related to the azimuthal phase structure of the beams and is quite distinct from any (spin) angular momentum due to polarisation. As discussed by Beijersbergen *et al*[2], orbital angular momentum may be transferred to a light beam by means of a cylindrical lens. This arises from the force on the dielectric material of the lens when it is placed in a light field gradient.

Recently[3], we have shown that elliptical Gaussian beams with general astigmatism[4] can possess orbital angular momentum as high as $10,000\hbar$ per photon. Such beams are easily produced from a standard TEM_{00} Hermite-Gaussian mode.

In this paper we discuss an experiment that is currently being conducted in our laboratory with the aim of demonstrating that elliptical Gaussian beams with general astigmatism can possess orbital angular momentum, by transferring this angular momentum to a microscopic particle suspended in a Paul trap. The experimental layout is shown in figure 1. This should form the basis for the study of orbital angular momentum in a trap and allow the investigation of new effects associated with off-axis absorption.

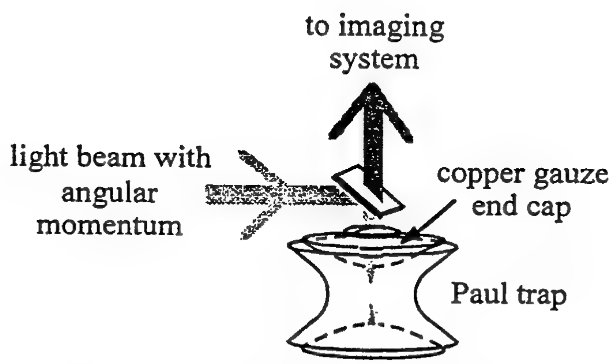

Figure 1: The experimental configuration

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GENERATION OF HIGHER-ORDER LAGUERRE BEAMS WITH HIGH EFFICIENCY COMPUTER GENERATED HOLOGRAMS

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In recent years, the production of Laguerre-Gaussian (LG) laser modes has attracted considerable interest. This interest arose largely from the prediction that these modes have an azimuthal phase term of $\exp(il\phi)$ which leads to a well defined orbital angular momentum equal to $l\hbar$ per photon[1].

The LG modes may be produced directly from a laser or, more usually, by the conversion of Hermite-Gaussian laser modes. The cylindrical lens mode converter[2] can be used to create LG beams of any order but requires a high order Hermite-Gaussian mode as the input. As an alternative, computer generated phase holograms[3] produce LG modes directly from the TEM_{00} mode allowing the use of a commercial laser source which consequently increases the ease of production. To date, however, holograms have only been used to generate LG modes with a radial mode index of zero.

In this paper we present the highly efficient (> 40%) generation of higher order Laguerre-Gaussian beams using blazed computer generated holograms. The beams produced are a superposition of LG modes with the same azimuthal mode index l but different radial mode indices p. By designing holograms with radial phase discontinuities the relative contributions of modes with different radial mode indices can be changed. As much as 80% of the output intensity can be associated with one mode index. Figure 1 shows a hologram design and the intensity profile of the resulting beam.

This highly flexible way of producing high power LG modes of arbitrary order will be used in a planned investigation into parametric down conversion processes.

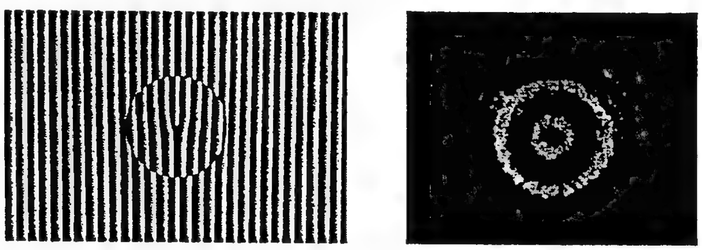

Figure 1: Design of hologram and resulting intensity profile of high order Laguerre-Gaussian beam

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HYBRID WAVEGUIDE-UNSTABLE RESONATOR FOR Nd:YAG PLANAR WAVEGUIDE

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A hybrid waveguide unstable resonator has been used with a planar waveguide Nd:YAG slab pumped by quasi-cw diode laser bars. The slab shaped geometry reduces thermal gradients to effectively one dimension, thereby increasing the thermal fracture limit of the gain medium and allowing higher power output per unit volume. The planar waveguide (reported earlier [1]) is a composite 200 μm Nd:YAG (1% doped) active region diffusion bonded to undoped YAG crystal. The slab is faced pumped using uncollimated diode laser light in a highly reflective cavity. The scheme uses multipass pumping to achieve the necessary absorption and gain in the active region. Results presented here are for a pump energy of 225 mJ with an output energy of 21 mJ.

Confocal unstable resonators allow efficient power extraction from large area devices in a collimated diffraction limited beam, while obtaining good mode discrimination against higher lateral modes. The unstable resonator employed is a confocal positive branch off-axis geometry with a magnification of 1.16 and a geometric output coupling of 15% (Fig. 1). Beam quality measurements used a 50 cm lens and the 95.4% power-content radius with the data fitted to the hyperbolic curve. The M^2 was determined for both lateral (unstable) and waveguide axes.

The beam in the lateral unstable axis has M^2=1.5 (Fig 2) and is highly collimated, thereby confirming the confocal condition for a resonator of this type.

An M^2=4.3 was found for the waveguide direction. The M^2 value depends on waveguide modes which can be selected by varying the distance between the mirror and waveguide. Near and far field beam profiles for the waveguide axis show a significant amount of light in the cladding which can affect the M^2 of the beam.

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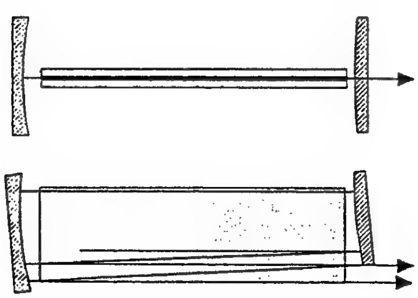

Figure 1. Hybrid waveguide-unstable resonator

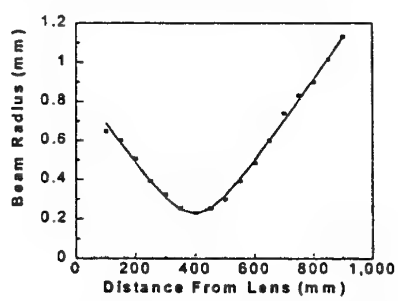

Figure 2. M^2 measurement for lateral axis

HIGH NUMERICAL APERTURE PLANAR WAVEGUIDES

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Rare earth doped planar crystal waveguides have the potential to yield efficient compact diode pumped lasers and amplifiers. Confinement of pump and signal to the waveguide core leads to high small-signal gains for amplifiers and, if additional propagation losses are small, low laser thresholds. The planar geometry is well matched to the asymmetric output of high average power diodes, simplifying the coupling and mode-matching requirements. The natural slab geometry is also ideal for thermal management. Coupling the highly divergent output of high power diode lasers into waveguides, either by focussing or proximity coupling, requires relatively thick waveguides (>10μm) and, especially for proximity coupling, a high numerical aperture (NA). We report two fabrication methods that can meet these requirements; pulsed laser deposition (PLD) and thermal bonding. The fabrication details and waveguide characterisation, including Ti:Sapphire pumped laser operation, will be discussed.

PLD is a versatile and relatively simple method of fabricating thin films of various crystalline materials. Despite being limited by lattice matching considerations, substrate and core materials of quite different refractive index can be combined to give a high NA guide. The guides reported here consist of a Nd:GGG thin film on a YAG substrate (an NA of 0.75) and were fabricated at F.O.R.T.H., Crete. Laser operation at 1.06μm and 0.94μm was obtained with a performance consistent with propagation losses of 0.5dB/cm, an order of magnitude improvement on that previously reported.

In contrast to PLD, the thermal bonding technique is not limited to lattice matched materials and so an even wider variety of dissimilar materials may be combined to create very high NA guides. The resultant waveguide also has spectroscopic properties identical to that of bulk material. The requirement here is to optically contact precision finished crystal or glass components, then apply heat treatment to increase their bonding strength and thus create the composite waveguide. Three different guides (fabricated by ONYX Optics, USA) are reported: (1) a low NA Nd:YAG on YAG guide, (2) a Nd:GGG on YAG guide, as used in the case of PLD, and (3) a Nd:YAG on glass guide demonstrating that very dissimilar materials can be bonded. This is necessary in the case of a Nd:YAG core due to its relatively low refractive index compared to other garnets. The laser performance of these guides in the 1.06μm region is consistent with propagation losses of 0.6dB/cm.

OPTICAL PROPERTIES AND LOCAL STRUCTURES OF GALLIUM LANTHANUM SULPHIDE / OXIDE THIN FILM FOR WAVEGUIDE LASERS

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Rare earth doped glass waveguides have recently received considerable attention because of their potential in the realization of active waveguide devices. Such devices offer a possible means of incorporating sources and amplifiers into integrated optical circuits.

We have used pulsed laser deposition technique to grow GALAS thin film waveguides in an oxygen atmosphere. The flow rates of the oxygen, and hence it's partial pressure, were adjusted to vary the content of oxygen in the film. The base pressure was about 4×10^{-7} Torr and the total chamber pressure during the deposition was about 10m Torr.

In this presentation, we report the effect of oxygen on optical and structural properties of GLS thin film waveguides. Incorporation of oxygen into GLS results in a decrease in Urbach absorption and, hence the waveguide losses . A preliminary EXAFS result shows that the oxygen bonds to all three elements present and the system appears to be chemically ordered. Optical absorption measurements are also reported and the results discussed and correlated with the structural data.

We have also investigated the effect of annealing on the optical and structural properties of GLS thin film. The effect of the annealing is that the optical gap increases and the absorption edge shifts to higher energy. this may be due to the breakage of the homopolar bonds and formation of heteropolar bonds in GLS thin film network.

QUASI-MODES OF PERIODIC SEGMENTED WAVEGUIDES

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Periodic segmented waveguides (PSWs) have recently received a great deal of interest. These structures have been used as mode converters [1], asymmetric couplers to provide wavelength filters [2], asymmetrically branched Y-junctions to achieve wavelength splitting for wavelength division multiplexing applications, [3] and Bragg-gratings [4].

In a PSW the increase in refractive index is periodically modulated. To study the propagation of light in channel PSWs a Three Dimensional Explicit Finite Difference Beam Propagation Method (3D EFD BPM) has been used. The periodic modulation of the refractive index induces a modulation in the intensity of the light propagating in the PSW (see Fig 1). The intensity distribution repeats every period, with a reduction in the amplitude due to radiation losses. For this reason we term the intensity distribution along a period the quasi-mode of a PSW (see Fig. 1). The light will converge when travelling through the areas with higher refractive index, and diverge when passing through the areas in between. This process is responsible for spatial broadening of the intensity profile. Radiation will be produced when the wave crosses the boundaries between the unconfined and confined regions, as can be seen in Fig 1.

The 3D EFD BPM has been used to compare the mode sizes of a PSW and of an equivalent continuous waveguide with an average index difference given by the weighted average of the refractive index along the propagation direction. We found good agreement between both sets of results, but only the actual PSW can provide us with information about the radiation loss.

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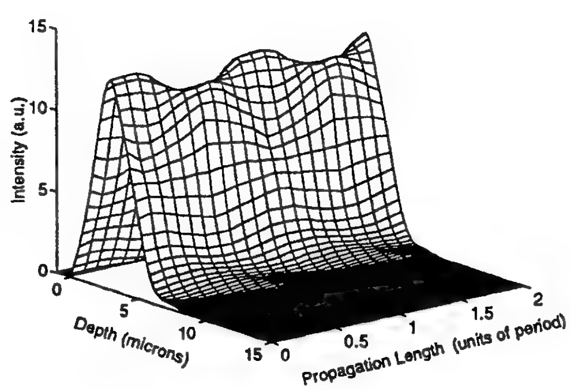

Fig. 1. Depth intensity profile along two periods of a step index channel PSW of period 17.5 μm, duty cycle 0.5, width 5 μm, depth 5 μm and an increase in the refractive index of 0.0215. The operating wavelength is 1.55 μm. The intensity profile was calculated by adding all the intensity points in the transversal direction for a given depth.

CONFINING ELECTRONS AND PHOTONS

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A new method has been derived for calculating the eigenstates and Green's function for electrons or electromagnetic waves confined by fairly hard boundaries. In this method the boundary is replaced by an embedding potential added to the wave equation, and the wavefunction can be expanded in any convenient basis set [1]. The method is applied to studies of waveguides with corners of different geometries, and the scattering properties of the waveguides are calculated. As an example a circular 90° bend is shown in figure 1. Figure 2 shows the transmission probabilities as a function of energy for a bend with internal radius $\rho=0.2W$. The conductance in the case of electrons is also calculated.

This method has the advantage of being completely flexible, and can be applied to arbitrary structures in 2 or 3 dimensions. Further applications include studying beam splitters and calculating the losses in dielectric systems .

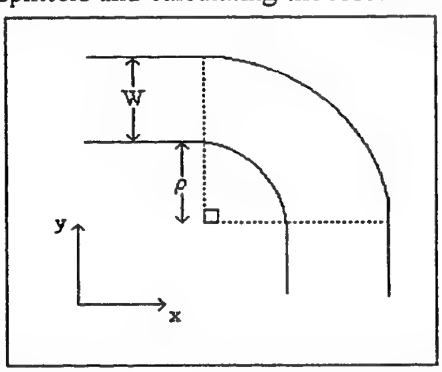

FIG. 1. Schematic of a 90° circular bend.

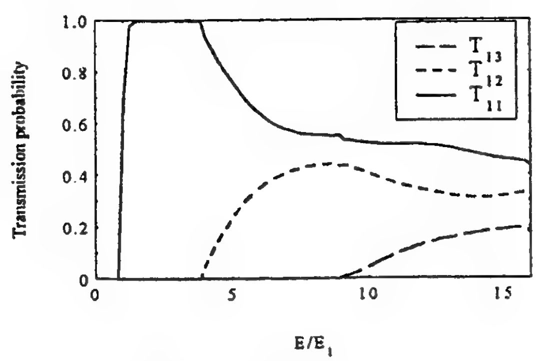

FIG. 2.Transmission probabilities between channels m and n plotted as a function of energy relative to the lowest energy eigenvalue.

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7. Applications

A NEW METHOD FOR HIGH SPEED IMAGING OF PARTICLES WITHIN INTENSELY RADIATING PLASMAS

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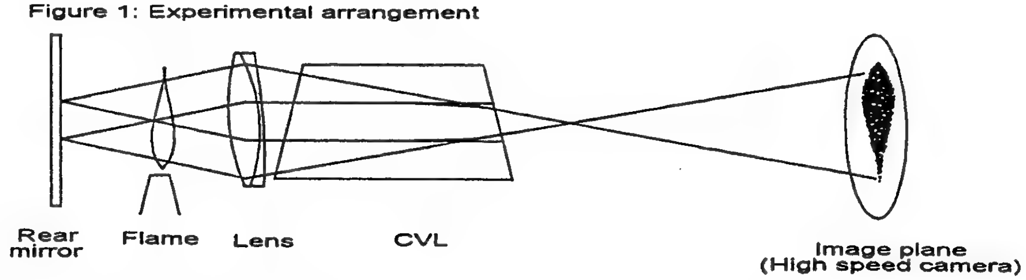
The copper vapour laser (CVL) is a very powerful tool in high speed imaging due to its capability for delivering short pulses over a wide range of pulse repetition frequencies (single-shot operation up to 40 kHz). With pulse durations of around 30 ns, image blurring is negligible even for objects moving at high speeds, while a variable pulse repetition frequency allows a large dynamic range of velocities to be monitored. However, up to date high speed imaging could not be applied satisfactorily to objects in very bright surroundings. We now employ an additional feature of the CVL, namely its ability to act as a high gain (10^4-10^6 per single pass) *narrow band* amplifier enabling us to discriminate against very bright broadband background emission. This is of particular interest, for example, for imaging particles in a hot plasma torch.

The optical set-up is based on the principle of a laser projection microscope (LPM[1]), where the laser provides both target illumination, using the single-pass amplified spontaneous emission (ASE) output, and acts as a brightness amplifier for the light scattered back from the object. In the present set-up (figure 1) however, the single-pass ASE is reflected by a rear mirror to form a shadow image of the objects. Since only laser light of the atomic Cu transitions (510.6 & 578.2 nm) is amplified, the bright background is eliminated and particles inserted into the flame of a vacuum plasma spray (Plasma-Technik AG Switzerland) appear as well-defined shadows in the image plane. A wide range of magnifications (usually of order 50) can be achieved. By employing this shadow-LPM technique, it was for the first time possible to perform high speed imaging of particles (in this case of 10 - 100 μm diameter) in a bright plasma torch. The field of view was 1.5 cm x 1.5 cm while the laser was run at a pulse repetition frequency of 25 kHz to allow velocities of up to 100 m/s to be analysed. We will present further details of the system as well as the results obtained.

Figure 1: Experimental arrangement



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PARTICLE CHARACTERISATION FROM FLUCTUATIONS IN POLARISED RADIATION

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The problem of small particle characterisation is of interest to a number of areas of industry. This paper presents methods of such characterisation by means of measuring the polarisation fluctuations in radiation scattered from an ensemble of scatterers.

It is known that radiation measured from scattering in the non-Gaussian regime and the correlations of polarisation fluctuations both contain particle characteristic information. These two facts are combined and utilised in the current work. Theoretical results for the fluctuations and the full probability density functions are obtained by using a dipole model for the scattering cross-sections of shaped particles and a random walk model for an ensemble of such particles. The results for these quantities are then solved for the purpose of determining particle shape and mean number density.

Diffractive Phase Elements for High-Efficiency Pattern Formation Tasks

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Diffractive phase elements (DPEs) are characterised by high-efficiency, and an optical functionality which far surpasses that of conventional optics. Many DPEs have been demonstrated performing intensity-sculpting tasks for applications such as display, laser-welding and material processing. In the latter case, diffractive elements are especially valuable when dealing with many high-power laser systems due to the very high laser damage threshold of applicable substrates. Suitable materials include SiO_2 for UV to near-infrared and ZnSe, Ge and Si for infrared. The photo-lithographic capabilities at Heriot-Watt University allow the fabrication of multi-level structures containing micron-scale features.

Typically, DPEs must be encoded in a distinct geometrical form to enable fabrication, e.g., as a pixellated structure. Discontinuities in this physical structure cause further diffraction effects at the output that reduce the performance of the element. We modify the design process to correct for the pixellated encoding-geometry, increasing image fidelity. Efficiency loss, which is only usually large for off-axis pattern formation, cannot be corrected in this manner. A new phase-encoding geometry is presented for off-axis pattern formation that results in reduced efficiency loss. This encoding geometry can be applied without a significant increase to the design difficulty or speed.

A number of 8-level DPEs are demonstrated performing useful beam-shaping and display tasks. Two examples are shown in figures 1 and 2. The efficiency of the elements are typically ~85% for on-axis, and ~75% for off-axis, excluding Fresnel losses in both cases.

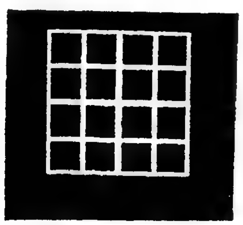

Figure 1. On-axis grid pattern

Figure 2. Off-axis 'HWU' pattern

Multi-colour images are more impressive in display applications than their monochrome equivalents. We present a novel design process for a DPE that operates under illumination with sources of two specified (visible) wavelengths. A fabricated element will be demonstrated that reconstructs two-colour patterns when illuminated with co-incident He-Ne (red) and He-Cd (blue) lasers.

High-efficiency Detection of Single Photons at Picosecond Resolution for use at Telecommunication Wavelengths

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The high-efficiency detection of single photons by semiconductor-based detectors at picosecond temporal resolution is of great significance for a number of applications in the strategically important wavelength range of 1.1μm to 1.6μm. For example, use of photon counting in picosecond time-resolved photoluminescence (TRPL) measurements on semiconductor material and devices at these wavelengths [1,2] has led to the study of carrier dynamics in these samples at low photo-generated carrier densities (e.g. $<10^{15}cm^{-3}$). Also, quantum cryptography [3], which enables the secure distribution of cryptographic keys across telecommunication networks [4] relies on sending the key at the photon per bit level (or less on average). The crucial component in a quantum cryptography system is a high quantum efficiency photon-counting detector capable of operation at a wavelength of 1.3μm or, preferably 1.55μm.

Single photon avalanche diode (SPAD) detectors are now widely used for single photon detection in place of photomultiplier tubes at wavelengths below 1μm. A SPAD is a photodiode biased at fields above breakdown, such that a single carrier can initiate a self-sustaining avalanche. Silicon SPAD detectors are now commercially available, with good room temperature performance at shorter wavelengths (ie< 1μm).

Currently, we have used Ge-based SPAD's over the wavelength range 1.1μm to 1.50μm, albeit at 77K to reduce thermally generated dark events [1]. The necessary cryogenic operation of such Ge SPAD's causes a significant shift in the absorption edge, such that only very low quantum efficiencies can be obtained at the important 1.55μm wavelength (i.e.<<1%). This has led to investigations of alternative long wavelength SPAD detectors, specifically those fabricated from InGaAs/InP, which show greater potential for operation at wavelengths of 1.55μm or above.

Results to be presented include characterisation of Ge-based SPADs and the application of these detectors in TRPL measurements of semiconductor material and devices at wavelengths of 1.3-1.5μm, and in prototype quantum cryptography demonstrators. Results of the characterisation of commercially available InGaAs/InP APDs biased above breakdown for use as SPADs will also be presented. A discussion of the design, fabrication and characterisation of InGaAs/InP devices specifically for photon-counting use will also be presented.

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The Measurement of the Wavefront Quality of the VULCAN Laser System
- Adaptive Optic Possibilities -

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ABSTRACT

VULCAN is a multi-beam ultra high power Nd:glass laser system that is capable of amplifying sub pico-second pulses to high energies using CPA. Typical power densities achieved in CPA mode are in excess of 10^{19} Wcm^{-2}. VULCAN is currently undergoing an upgrade to increase this to 10^{20} Wcm^{-2}.

An important parameter of the laser system is the output wavefront since this limits the focusability of the beam. Additionally, wavefront quality also places a lower limit on the shortest pulse duration that is achievable by the CPA technique.

We have recently determined an approximate measure of beam wavefront quality by pinhole transmission measurements, indicating that the current focusability of VULCAN is a factor of 3 worse than a theoretical diffraction limited performance.

We have therefore undertaken a detailed study of the wavefront quality of a number of the large aperture beams of the system to determine the nature of the phase errors that are leading to the current 3 times diffraction limited performance. We present the results of this investigation. We pay particular attention to whether the errors are fixed (optics origin), slowly varying (thermal origin) or transient (only appear on the laser shot).

Finally we outline details of an adaptive optics programme that we have instigated to address the correction of these errors on a real time basis. We hope this will result in a wavefront performance closer to the diffraction limit.

PHOTOSENSITIVITY IN PHOSPHOSILICATE GLASSES CODOPED WITH TIN PRODUCED BY FLAME HYDROLYSIS DEPOSITION AND AEROSOL DOPING.

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In recent years, research into photosensitivity of doped silicate glasses has attracted much attention due to the potential applications it offers[1]. Photosensitivity allows the fabrication of UV induced Bragg gratings[2], laser trimming[3] and direct writing[4] of channel waveguides. The majority of this work has concentrated on GeO_2 and GeO_2-B_2O_3 doped fibres. However, when applications demand codoping with rare earth (RE) ions, germanosilicate glasses are not the ideal, since the solubility of the RE is low in this kind of host[4]. A better host is achieved by doping the silica with phosphorus and small amounts of aluminium[5]; but it is well known that the presence of phosphorus bleaches the absorption band centred at 240nm, and thus reduces the photo induced index change[6]. Since selective doping and wafer bonding are difficult to realise in the fabrication of silica-on-silicon integrated optics devices, it is important to have a host with good rare earth solubility and enhanced photosensitivity if, for example, the goal is the integration of a laser and a Bragg grating mirror.

We report the successful production of photosensitive layers of phosphorus-tin doped silica using FHD and aerosol doping [7], in analogy with a previous report on the fibres domain[8]. The absorption of the deposited layers was evaluated and the optimum concentration for the doping solution can be found. This is deduced by maximising the UV absorption whilst not creating additional scattering loss. It was observed that exposure to the UV output from a KrF excimer laser bleaches the absorption band centred at 248nm and increases the absorption at shorter wavelengths. We also show that is possible to enhance the UV absorption by flame brushing.

The authors would like to thank Dr. Andrew Glidle for the absorption measurements. P.V.S. Marques also acknowledges financial support from the Portuguese Research Council (JNICT), through the Programme PRAXIS XXI.

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AN INFRARED FOURIER-TRANSFORM SPECTROMETER BASED ON WOLLASTON PRISMS

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Previously we have reported the development of static Fourier-transform spectrometers based on Wollaston prisms. The Wollaston prisms form an interferogram in the spatial domain which can be recorded using a detector array. A subsequent Fourier-transform of this interferogram yields the spectral content of the illuminating light source.

In this paper we report on the extension of this technique to the infrared region of the spectrum. Using Wollaston prisms fabricated from magnesium fluoride it is possible to gain spectral coverage out to 7.5μm. Our previous design in the ultra-violet and visible regions of the spectrum have used silicon based detector arrays. Existing infrared detector arrays are considerably more expensive than their visible counterparts and hence, as a technology demonstrator, we have designed our new spectrometer around a single element PbSe detector. This detector results in a spectral response for our spectrometer of 1-4.5μm. The use of a single point detector requires us to scan the lateral position of the Wollaston prisms and record the interferogram as a function of time. More cost effective infrared detector arrays are currently being developed and when available will be incorporated simply into our existing instrument there by eliminating the need for moving parts.

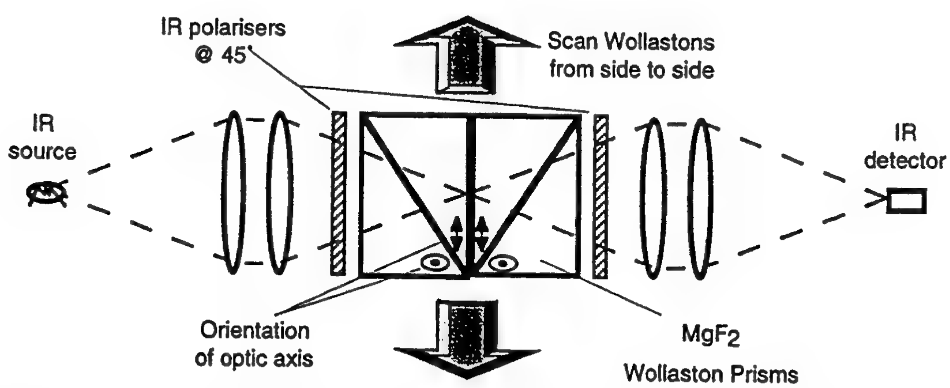

Figure 1. A schematic layout of the FTIR spectrometer based on Wollaston Prisms

AN ULTRA-COMPACT STATIC FOURIER-TRANSFORM SPECTROMETER USED AS A LASER WAVEMETER

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The development of a static Fourier-transform spectrometer based on one Wollaston prism, two polarisers, and a compact two-dimensional detector array is described. The Wollaston prism is designed such that for an extended light source the interferogram fringes are localised just behind the exit face of the prism onto the detector. Data processing of the resultant interferogram yields the spectral content of the illuminating light source. This leads to an ultra compact design where the wavelength calibration is fixed by the geometry of the prism and the detector array and is therefore inherently stable.

The spectrometer optics are configured within a $10mm$ cube. This cube assembly can be mounted in place of a lens in front of a standard video (CCD) camera, thus converting an imaging camera into a compact spectrometer. The device is interfaced to a desk top computer via a standard frame grabber card and run using windows based software, either as a general purpose laboratory spectrometer or as a laser wavemeter. The spectrometer operates in the visible region of the spectrum, has a resolution of $200cm^{-1}$, an aperture of $6.5 \times 5mm$, and a field of view of $\pm 5°$. Although of limited resolution, the inherent stability of the instrument means that the frequency of a monochromatic light source can be determined precisely. Using the spectrometer as a laser wavemeter, we have demonstrated a wavelength precision of better than 1 part in 10^5.

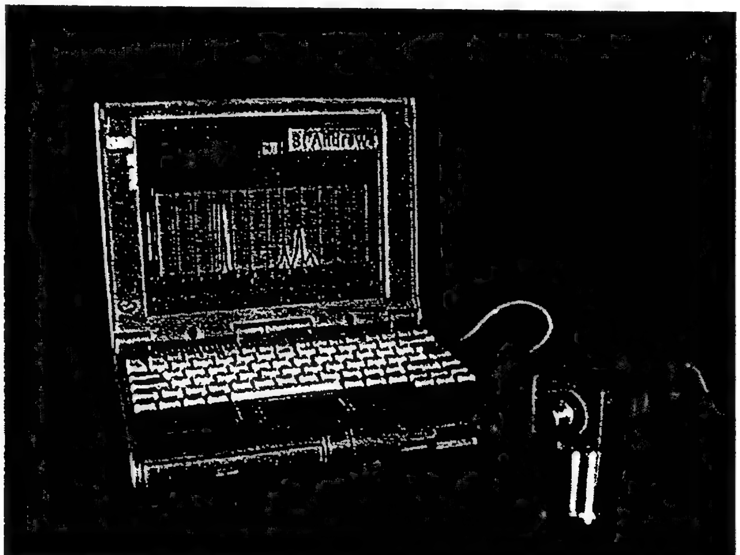

Figure 1. The compact spectrometer / wavemeter

Implementation of the *Optical Highways* General Purpose Parallel Computer Interconnect Scheme

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The *Optical Highways* [1] scheme is a design for an optical, free-space interconnect for massively parallel computers. Unlike some other optical interconnect schemes this design is not constrained to low-order networks but is a general purpose interconnect onto which almost any network topology can be mapped. For example, the Optical Highway can be configured to implement topologies such as a low-order *2-D Mesh*, a multi-dimensional *Hypercube*, or even a high-order *Crossbar*. This flexibility makes the scheme appealing to parallel computer architects, especially the ability to implement large-scale, higher-order network topologies, which were previously impossible using only conventional electrical interconnects.

The driving force behind this scheme is the great disparity between the possible space-bandwidth supplied by opto-electronic devices and that available within an optical relay system. Assuming the use of advanced GaAs fabrication techniques for the production of large arrays of multiple-quantum-well (MQW), quantum-confined stark-effect (QCSE) devices acting as high-speed opto-electronic modulators and detectors, then the maximum achievable space-bandwidth is of the order of 10,000 channels [2]. If well designed, diffraction-limited, multi-element bulk-optics are employed in the optical relay, then the maximum optical space-bandwidth will be in the region of 200,000 channels. (See figure below.) A description of the evolution of the optical and opto-electronic devices necessary for this system will be given.

By using carefully designed patterned half-wave plates and related spatial positioning of the transmitter/receiver pairs we show how the available space-bandwidths of both the optical and opto-electronic systems can be utilised fully. We compare various common interconnect topologies and show how these impact on the physical implementation of both the optics and the opto-electronics. This will lead to a number of possible designs for the system, which we shall contrast.

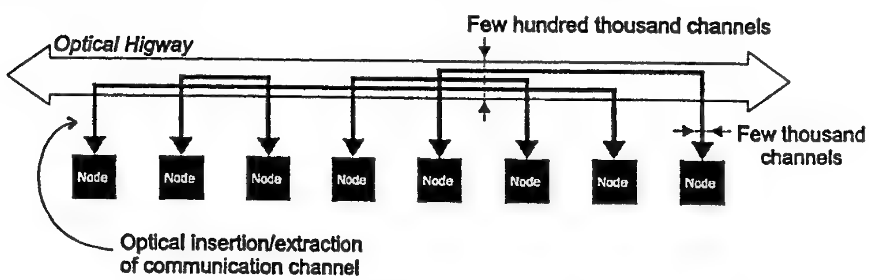

Figure 1: Schematic diagram of the *Optical Highways* concept.

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8. Solid State and Fibre Lasers

ULTRALOW-THRESHOLD KLM Cr^{3+}:$LiSrGaF_6$ LASER PUMPED BY A SELF-INJECTION-LOCKED AlGaInP DIODE LASER

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Major progress has been made in recent years regarding the production of femtosecond pulses from directly-diode pumped Cr^{3+}:$LiSrGaF_6$ (Cr:LiSGaF) and Cr^{3+}:$LiSrAlF_6$ (Cr:LiSAF) lasers [1]. These laser systems have produced femtosecond pulses at output powers equivalent to some mainframe argon-ion pumped Ti:Sapphire lasers. Much of the recent research, however, has centred around using broad-stripe, high-power diode lasers which require relatively intricate and extended coupling optics to reshape their rather poor quality, non-diffraction-limited beams. Our work has concentrated on investigating whether modelocking may be observed at the pump powers available from laser diodes having good quality single-spatial mode beams [2]. These diode laser beams may be readily coupled into the vibronic gain crystal using simple relay optics thereby providing the means to create a stable, cheap and compact source of femtosecond pulses. We have demonstrated the production of 100fs pulses from a 3-mirror, soft-aperture, self-modelocked Cr:LiSGaF laser pumped with 45mW from a self-injection-locked semiconductor laser and have observed Kerr-lens modelocking with pump powers as low as 20mW.

Our femtosecond laser system uses a novel 3-mirror cavity design to provide low CW and self-modelocking thresholds. The use of a near-diffraction-limited pump beam allows very tight focusing of the pump mode within the laser gain crystal thus increasing the efficiency of the soft-aperture self-modelocking and hence reducing the self-modelocking threshold. The laser crystal itself is a plane-plane, anti-reflection coated rod of Cr:LiSGaF for which the astigmatism experienced in conventional Kerr lens modelocked laser cavities has been avoided. Modelocking performance was optimised by carefully controlling the intracavity dispersion with low loss and low third-order-dispersion prisms. The pump laser used was a 100µm stripe-width, 0.5W, AlGaInP diode laser operating at 664nm. This diode laser was used in conjunction with a self-injection-locking scheme to produce a near-diffraction limited pump beam at powers up to 150mW. For pump powers around 100mW the pulse durations were typically ~70fs at avarage output powers ~3mW.

In summary, consideration of the factors affecting the power required for ultrashort pulse generation has led to the development of a compact low-threshold all-solid-state laser system based around the chromium-doped Colquiriite Cr:LiSGaF capable of producing ultrashort pulses with sub-50 mW pump powers. This laser may potentially be pumped by lower power, low cost, narrow-stripe, single- spatial-mode diode lasers.

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A CONTINUOUS-WAVE SINGLY-RESONANT INTRACAVITY OPTICAL PARAMETRIC OSCILLATOR BASED ON PPLN

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Intracavity singly-resonant optical parametric oscillators (ICSRO's) have recently been shown to be novel practical sources of amplitude- and frequency-stable continuous-wave (cw) radiation [1]. In this paper we describe a system which combines the intracavity approach with the high nonlinear coefficient of periodically-poled lithium niobate (PPLN) to provide an efficient, low threshold, cw source tunable in the infrared.

The PPLN crystal is pumped at the intracavity focus of a cw Ti:sapphire laser. The Ti:sapphire laser is itself pumped by a low power argon-ion laser or a diode-pumped frequency doubled Nd laser and is configured as a low-loss standing-wave cavity to optimise the multi-frequency intracavity power. An intracavity lens forms the tightly focused spot in the PPLN crystal in one arm of the cavity. The two mirror SRO resonator shares a common end mirror with the laser, and is separated from the laser cavity by a dichroic beamsplitter.

The 19mm long PPLN crystal contains 8 gratings with periods from 21.0μm to 22.4μm. These are consistent with quasi-phase-matched down-conversion of wavelengths of around 800nm into the infrared. The crystal temperature is maintained at 165.0°C in a servo-controlled oven to avoid photorefractive damage.

While maintaining the crystal at a constant temperature, the output of the SRO may be tuned by varying the Ti:sapphire wavelength or the grating period of the PPLN. The resonant signal wave tunes over the mirror bandwidth from 1073 to 1275nm with an idler range from 2.30 to 3.33μm. The idler tuning range is limited by the range of grating periods, with suitable gratings it may be extended from ~1.8 to ~4.5μm.

When pumped with 6W of argon-ion power, a total idler power of 280mW has been obtained. This corresponds to a total down-converted power of 75% of the optimum Ti:sapphire output. In the presence of parametric conversion the circulating intracavity laser field is clamped at the threshold value of 4.5W. The power performance is presently limited by thermal lensing in the PPLN crystal. We estimate that in the absence of parametric oscillation, an intracavity field of 30W forms a thermal lens in the PPLN crystal of 10mm focal length. With suitable compensation for the thermal lens, down-converted efficiencies approaching 100% of optimum laser output should be possible, as previously demonstrated in KTA [2].

We have extended the operation of the ICSRO to an all-solid-state configuration with the use of a diode-pumped frequency-doubled $Nd:YVO_4$ laser (*Spectra Physics Millennia*) as the pump source for the Ti:sapphire laser. With 5.3 W of input pump power and without optimisation, we have generated up to 120mW of idler power tunable over the above range. Progress with this arrangement will also be presented.

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STEADY-STATE AND TRANSIENT ANALYSIS FOR CONTINUOUS-WAVE INTRACAVITY SINGLY-RESONANT PARAMETRIC OSCILLATORS

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Intracavity singly-resonant optical parametric oscillators (ICSRO's) have recently been shown to be novel practical sources of amplitude- and frequency-stable radiation [1,2]. Such devices have received little attention since initial theoretical work [3] in the 1960's with intracavity doubly-resonant oscillators (ICDRO's) where it was found that, in addition to the resonance constraints normally associated with DRO's, these devices exhibit further instabilities at moderate pumping levels. We show here that ICSRO's do not suffer from the same problems of instability, though do exhibit novel transient behaviour, and as such represent practical continuous-wave sources capable of high output powers and conversion efficiencies.

A steady-state model, similar to that in [3], describes the operation of cw ICSRO's. The pump and signal fields are defined as resonant single axial modes of their respective cavities. They mix in the nonlinear medium to produce a single pass idler field whose axial amplitude variation is calculated from Maxwell's equations. The (much slower) temporal variations are assumed to follow those of the resonant waves. This assumption allows the adiabatic elimination of the idler field's own dynamics (*c.f.* [4]), reducing the analysis to that of the resonant waves. Nonlinear polarisations, projected onto the appropriate cavity modes, are calculated for each of the signal and pump fields. These, plus contributions from the laser gain medium, form the polarisation terms in a set of self-consistency equations [3].

The model yields three distinct regions of operation: I where there is no laser field, II where the laser field is present, but no parametric conversion, and III where parametric conversion occurs. It predicts clamping of the pump field in III, in agreement with experiment [1], and mode-pulling due to both laser and parametric gain media. A Liapunov analysis of the system shows that the steady-state of region III is unconditionally stable against any perturbation- the ICSRO will never exhibit the repetitively pulsing mode of the ICDRO.

The analysis predicts relaxation oscillations in the ICSRO even in the absence of laser oscillations. Such OPO relaxation oscillations are analogous to those of a laser with the upper-state lifetime replaced with a term involving the laser cavity lifetime τ_{cav}. The model shows the transition from laser- to OPO-dominated relaxation oscillations with varying τ_{cav}. Experimental work demonstrating OPO relaxation oscillations and stable ICSRO operation at pumping levels well above threshold will be presented.

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HIGH POWER DIODE BAR PUMPED Tm:YAG LASER AND INTRACAVITY PUMPED Ho:YAG LASER

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Tm^{3+} and Ho^{3+} doped lasers operating in the 'eyesafe' 2µm region have recently attracted growing interest owing to their numerous applications, particularly in LIDAR. For many LIDAR applications the higher atmospheric transmission around 2.1µm favours the Ho^{3+} laser over the Tm^{3+} laser at ~2.0µm, whereas the latter offers a more convenient wavelength for diode-pumping. The standard approach to overcoming this problem is to use laser crystals with Tm^{3+},Ho^{3+} co-doping, the Tm^{3+} being diode-pumped at 785nm followed by energy transfer to the Ho^{3+} ions upper laser level. This process works efficiently in cw-lasers, but upconversion effects substantially shorten the storage lifetime in Q-switched lasers.

This problem can be avoided using an intracavity pumping scheme with Tm^{3+} and Ho^{3+} ions separated into two different rods in the same cavity. The Tm^{3+} material can be directly diode-pumped at 785nm, while the Ho^{3+} material is pumped by the 2µm laser emission of the Tm^{3+}. The weak absorption of the Ho^{3+} (typically a few percent) acts as the 'output coupler' for the Tm^{3+} laser. Recently such an intra-cavity pumped laser has been reported[1], which had an output of 120mW with the Tm:YAG being pumped by a Ti:Sapphire laser. Here we report a diode-pumped system with multi-watt output.

Our approach makes use of the two-mirror beam-shaping technique recently reported[2], to reconfigure the output beam from a high-power diode bar so as to allow intense end-pumping with an essentially circular beam. Using this pump source we have demonstrated efficient room temperature operation of a Tm:YAG laser[3] with an output power of 4W for 13.5W of incident pump. The set-up for the intracavity-pumped Ho:YAG laser is shown in Fig.1 and is similar to that of the Tm:YAG laser. The pump input mirror has high reflectivity from 2.0 to 2.1µm, and output coupler is highly reflective from 2.00 to 2.02µm with 10% transmission around 2.1µm. For 9.2W of diode power incident on the Tm:YAG rod the maximum output was 2.1W at 2097nm corresponding to a slope efficiency of 28%. The Tm:YAG laser itself operated at 2012nm. The threshold for Tm:YAG lasing was 1.5W, while the Ho:YAG started lasing at the slightly higher diode power of 1.7W.

Appropriate modifications to the resonator design and optimum choice of dopant concentrations should bring significant further improvements in performance.

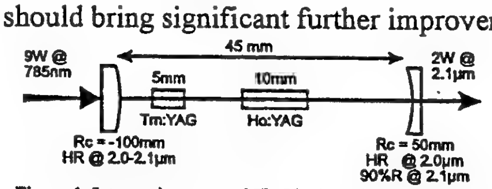

Figure.1. Intracavity pumped Ho:YAG cavity arrangement

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FEMTOSECOND-PULSE GENERATION FROM A Cr^{3+}:$LiSrAlF_6$ LASER PUMPED BY A LOW-POWER SINGLE-STRIPE AlGaInP DIODE LASER

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A major driving force behind much of the commercial laser development in recent years has been to reduce the complexity and relative costs of laser systems. The ultimate in simplicity for a Kerr-lens modelocked (KLM) laser system has long been regarded as a compact cavity, pumped directly by a narrow-stripe, single-spatial-mode laser diode. We have demonstrated ~200fs pulse operation from a laser of this type, to our knowledge the first of its kind.

The laser was pumped with a Spectra Diode Labs SDL-7311-G1, diffraction-limited, narrow-stripe laser diode with a maximum output power of 33mW at a wavelength of 682nm. This power is less than the CW threshold of other diode pumped femtosecond lasers. The beam from the diode laser was collimated using a standard laser diode collimating lens and was focussed into the vibronic gain crystal through the retroreflecting end mirror using a 5cm lens. This provided a very simple and straightforward pump arrangement as no other special coupling optics were required.

The laser gain media was a 7mm Brewster angled crystal of Cr^{3+}:LiSrAlF. The high reflectivity mirrors were arranged in a 3-mirror asymmetric cavity geometry, which comprised a 50mm r.o.c. retroreflecting end-mirror, a 75mm r.o.c. folding mirror and a plane end mirror. The laser cavity also contained a low-loss dispersion-controlling Infrasil prism and a prism-based, acousto-optic modulator, which was used to regeneratively initiate the modelocking. The cavity geometry allowed the laser mode to be tightly focused (10-15μm spot size) on to the crystal facet adjacent to the retroreflecting end-mirror. This ensured that low CW and low self-modelocking thresholds could be established.

The CW lasing threshold was 9.3mW and the modelocking threshold was observed to be 23mW. This laser produced near-transform-limited modelocked pulses with ~200fs pulse durations.

In addition to presenting the above results the modelocking performance of successive versions of this diode-pumped Cr:LiSAF laser will also be discussed.

HIGH EFFICIENCY SECOND HARMONIC AND SUM FREQUENCY GENERATION OF NANOSECOND PULSES IN A CASCADED ERBIUM DOPED FIBRE:PPLN SOURCE

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Recently, femtosecond erbium fibre lasers have been used with periodically poled lithium niobate(PPLN) to demonstrate frequency doubling with up to 25% conversion efficiency[1], and using the second harmonic, to pump an Optical Parametric Generator (OPG)[2]. However, for many applications e.g. pumping of nanosecond Optical Parametric Oscillators (OPOs) pulses with greater energies are required, for which diode-pumped, large mode-area erbium doped fibre amplifiers (LA-EDFA) and lasers are ideally suited[3]. The combination of diode-pumped, LA-EDFA sources with periodically poled lithium niobate creates an extremely attractive technology for the development of a wide range of practical wavelength tuneable sources.

In this work both diode-seeded LA-EDFA chains and Q-switched sources were used to demonstrate extremely high second and third harmonic single pass conversion efficiencies in PPLN. Continuously tunable operation over the erbium gain bandwidth was demonstrated with pulses from 2 to 50ns, repetition rates from 1kHz to 150kHz, and pulse energies of up to 50μJ.

Output pulses at a fundamental wavelength of 1536nm were frequency doubled in PPLN, to produce 768nm light with internal conversion efficiencies as high as 83% in a single pass for a peak power of 1.2kW. A second PPLN crystal was used to mix the second harmonic with the remaining fundamental to generate green light at 512nm, with up to 34% internal conversion efficiency. Both PPLN samples were 16mm long and fabricated in 0.5mm thick z-cut lithium niobate by electrical poling. The periods were 18.05 μm for SHG and 6.5μm for sum frequency generation.

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POLARIZATION EIGENMODES OF A Nd:YVO_4 / KTP INTRACAVITY FREQUENCY-DOUBLED MICROCHIP LASER

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Abstract:
A microchip laser typically consists of a sub-millimetre thickness slice of solid state laser gain material, polished plane parallel, with suitable dielectric mirrors coated directly on to it. This device is then longitudinally pumped by a diode laser and pump induced lensing mechanisms induce a stable cavity.

This basic design can modified by the addition of a second crystal to the device. If the second crystal is placed in contact with the laser gain material and the coatings are placed on the outside faces of the crystals, a low loss cavity is realised. If the second crystal is a saturable absorber then a passively Q-switched laser can be produced [1] or if, as in this paper, a suitable non linear crystal is used, efficient frequency doubling can be demonstrated [2].

The laser described here consisted of a 0.5mm thick slice of 3% doped Nd:YVO_4 and a 2mm thick slice of KTP cut to realise type II phase matching for the conversion of the fundamental at 1064 nm to high quality green light at 532 nm. This group has demonstrated that when such a laser is pumped with a 650 mW of diode laser pump power, 132 mW of TEM_{00} green light can be produced [3].

Despite the intrinsic simplicity of the design and the lack of adjustable components as compared to an extended cavity laser, good power stability of the green light can be observed even though the laser may be operating on two cavity modes. Hence, as a first step to understanding why no "green problem" is observed over a wide range of operating conditions, it is important to consider the formation of longitudinal and polarization modes in the cavity. This was approached in two ways. Firstly the cavity was modelled using a Jones calculus approach. This model was used to predict the behaviour of the infra-red modes on temperature tuning of the whole cavity. The output wavelengths and the polarizations of these modes at the input and output couplers can be extracted from this model. Secondly experimental work was undertaken to measure these parameters. It was found that over a range of temperature of 35 °C, the wavelength tuning and polarization rotation of the IR modes could be accounted for.

This analysis forms a starting point for building better understanding of the microchip green laser because the polarization and wavelength of the modes will impact on an understanding of the doubling process in terms of efficiency and any coupling between the modes.

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HIGH-POWER BLUE LIGHT GENERATION IN PERIODICALLY-POLED LITHIUM NIOBATE

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Frequency doubling of the 946nm line of Nd:YAG offers a possible route to the generation of high average power in the blue, with an all-solid-state technology. Recent results include the generation of 410mW at 473nm by intracavity frequency doubling using $KNbO_3$[1]. Periodically-poled lithium niobate (PPLN), with its combination of high nonlinearity and non-critical phase-matching offers the prospect of high conversion in a simple, extra-cavity single-pass arrangement. A previous demonstration [2] with PPLN gave 49mW of 473nm power, although the blue beam quality was significantly degraded at this power level by the photorefractive effect. Here we report an order of magnitude increase in mean blue power, without any sign of beam degradation.

We prepared the PPLN sample, of 15mm length, 0.5mm thickness, grating period 4.5μm, by electric-field poling through a photolithographically patterned photoresist on the -z face. The period was chosen for phase-matching at an elevated temperature of 140°C, thereby greatly reducing the photorefractive effect. The phase-matching temperature bandwidth, measured as 1.2K, is consistent with the 15mm crystal length.

The fundamental laser source was a Nd:YAG laser pumped by a single, beam-shaped 20W diode-bar. The Nd:YAG resonator was chosen to provide compensation for the strong lensing that occurs as a result of intense pumping. This laser has produced a cw power of 2.1W in a linearly polarised fundamental mode ($M^2<1.1$). However, in these harmonic generation experiments average powers in the 1 - 1.5W range were used, with the laser operating with a regular pulsed output at the relaxation oscillation frequency (160kHz, 300nsec pulses). This behaviour was induced via feedback from the uncoated PPLN surface, together with a piezoelectrically driven dither of the output coupler.

Under these conditions, with an average fundamental power of 1.13W inside the PPLN, focussed to a spot radius of 30μm, a generated blue power of 450mW, corresponding to 40% conversion efficiency, was obtained. The output blue beam had a circular profile with measured M^2 values of $M_x{}^2 = M_y{}^2 \approx 1.25$, indicating that photorefractive effects were not significant at this average power/intensity level for the 140°C temperature of operation. There is also no sign of roll-off from the quadratic relation between harmonic power and fundamental power. These results suggest that with attention paid to optimisation of the laser, and with provision of coatings for the PPLN crystal, blue powers exceeding 1W should be achievable in this way.

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PASSIVE Q-SWITCHING OF ND:YVO_4 MICROCHIP LASERS

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Microchip lasers are typically formed by applying dielectric mirrors directly to two near-parallel surfaces of a thin slice of laser gain material. Nd:YVO_4 is a commonly used gain material because of its short absorption depth, high stimulated emission cross section and reasonable upper state lifetime (55us).

By forming a composite microchip laser using a piece of Nd:YVO_4 and a piece of Cr:YAG, it is possible to passively Q-switch these devices, through the intensity dependant absorption of the Cr^{3+}, to give high peak powers (>1kW) and short pulses (<1ns) [1]. Much of the work on these devices has been based on Nd:YAG, because of its longer upper state lifetime (~230us), which allows greater energy storage [1]. We demonstrate what we believe to be the first passively Q-switched microchip lasers based on Nd:YVO_4 which have the potential for higher repetition rates than equivalent Nd:YAG devices.

We have modelled the behaviour of these devices using the work of Xiao and Bass, which indicates for Cr:YAG with 85% small signal transmission, we would expect pulses of 130W peak power and pulse widths of 2.7ns. Experimentally we observed peak powers of 243W and widths of 4ns because of lower than expected parasitic losses. The pulse period was found to be 55-60us in agreement with the expected value.

We have examined the effect of different Cr^{3+} densities in Cr:YAG and found that 85% small signal transmission represents a near-optimum value, though higher concentrations giving 80% transmission give a more stable output with less than 5% fluctuation in the period and intensity of the Q-switch pulses produced. Cr:YAG with 90% transmission was found to give insufficient loss to prevent lasing, though produced high frequency (1-5MHz) pulses with low peak powers (~1W).

We will present work on the frequency doubling and the effect of changing the output coupling of these devices to determine the optimum setup and operation.

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Polarisation Control in Top-Surface Emitting Vertical Cavity Lasers by Post Processing Using Focused Ion Beam Etching

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Vertical-cavity surface-emitting lasers (VCSELs) are attractive sources, particularly suited to applications requiring two-dimensional laser arrays. However, if they are to be deployed in polarisation-sensitive applications, such as magneto-optic recording and coherent detection systems, methods of controlling the polarisation state of emission of the VCSEL are required. In GaAs-based devices, the orientation of the dominant polarisation state may be random, and orthogonally polarised modes may co-exist. Methods to control the polarisation state of emission include the use of anisotropic cavity geometries or by introducing an anisotropic stress. Typically control is usually maintained only near threshold and anisotropic cavities can affect the beam shape. External structures may be combined with the VCSEL for polarisation control, though this increases the number of system components and hence complexity. More recently, growth on misoriented substrates has been shown to pin the polarisation along a fixed crystal axis.

In this work we report a simple robust and reliable technique for complete polarisation control of VCSELs across their entire operating range. This is achieved in standard VCSELs by post processing using focused ion beam etching (FIBE) to place a line etch near the cavity aperture. High spectral quality circular output beams are maintained. The technique is valid for different device diameters and structures and the etch dimension tolerances should allow a single etch process to reliably pin the polarisation state of all devices on a wafer.

Polarisation control is achieved by etching trenches 1μm wide and just over 2.5μm deep which are placed between 1 and 2μm from the cavity aperture through the top gold contact so as to minimise its impact on the spatial emission of the VCSEL. The depth of the etch is carefully controlled to prevent degradation of the electrical characteristics of the device. Prior to etching, the polarisation axes of a number of the devices investigated have been found to be defined by the crystal axes though they are randomly oriented in others. However, after etching, in all cases the polarisation axes are found to be determined by the etched trench, irrespective of its orientation to the crystal axes. The degree of polarisation control is found to be dependent on the etch depth and its proximity to the active region. An optimum etch depth into the top mirror exists for which the polarisation state remains fixed throughout the device bias current operating range, with the dominant polarisation normal to the etch direction. For a large area GaAs device, the pre- and post-etch polarisation ratio characteristics are shown in figure 1. Prior to etching, the higher order transverse modes are orthogonally polarised to the fundamental mode, which restricts the operating range over which a high polarisation ratio is obtained. However, the effect of the etch is to suppress the emission in one of the polarisation states forcing the polarisation state of all modes to be pinned. Single polarisation emission is then achieved over the entire operating range of the lasers, without degradation of the power output. Since the etch does not cross through the cavity aperture, high spectral quality circular output beam characteristics are still achieved.

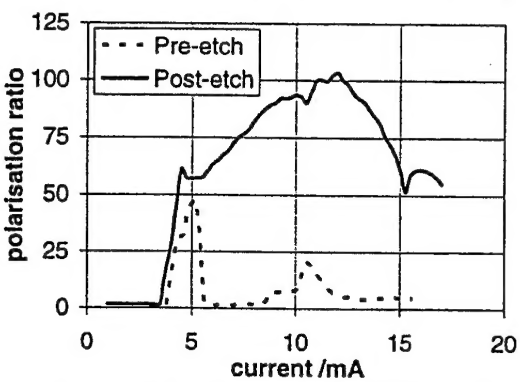

Figure 1: Effect of etching on polarisation ratio.

It is believed that the etch introduces an additional cavity effect through, for example, a lateral polarisation-dependent reflectivity which modifies the optical mode density and the coupling of the spontaneous emission into the two orthogonal polarisation states. The strong polarisation dependence of the spontaneous emission at the etch feeds back into the laser cavity and mode formation is then influenced by the polarisation dependence of the spontaneous emission, forcing all modes into a single polarisation state.

In summary, full polarisation control of VCSELs is achieved using FIBE to determine the dominant polarisation axis for all transverse modes, and a high output beam quality is maintained, with no degradation of the electrical characteristics of the device.

Further results assessing the etch parameters and the polarisation pinning mechanism will be presented.

QE 13

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